ASSESSMENT OF CROSS LAMINATED TIMBER MARKETS FOR HARDWOOD LUMBER

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ABSTRACT

The goal of this study was to assess the potential of using hardwood lumber in CLT manufacturing. The goal was achieved by addressing four specific objectives. The first objective was to collect CLT manufacturers' perspectives for using hardwood lumber in the current manufacturing setup. The second objective was to determine hardwood sawmills' current ability to produce structural grade lumber (SGHL) from low value logs as a product mix through a survey of hardwood lumber producers in the US. The third objective was to conduct a log yield study of SGHL production from yellow poplar (YP) logs to produce 6" and 8" width SGHL to match the PRG 320 requirements. The fourth objective was to determine CLTs' production cost using SGHL and compared it with the CLTs manufactured from southern yellow pine (SYP).

The results suggest that all three CLT industries visited and interviewed had sufficient technology to produce hardwood CLTs. The production of hardwood CLTs was mainly limited by the quality and quantity of lumber available. The hardwood sawmill survey results indicated that, currently, less than 10% of the sawmills had all the resources required to produce SGHL. The current ability of the sawmills was measured based on the resources necessary to begin SGHL production. Forty percent of the sawmills would require an investment in sawing technology to saw SGHL, 70% would require employing a certified lumber grader, and 80% would require a planer to surface lumber. Another significant finding was the sawmills' willingness to collaborate with other sawmills and lumber manufacturers. More than 50% of sawmills were open to potential collaboration with other stakeholders if necessary, which is crucial to commercializing SGHL for a new market.

The log yield study of yellow poplar helped demonstrate that the mixed grade lumber production method to convert lumber from lower quality zones as SGHL yields higher lumber volume for sawmills and at the

same time reduces lower-grade lumber volume. On average, SGHL production increased lumber volume by more than 6% compared to only NHLA grade lumber production when 65% of the lumber was converted to SGHL. The volume of lower lumber grades from 2 common and below decreased from an average of 85% to less than 30% when producing SGHL as a product mix with NHLA grade lumber. This study observed more than 95% of SGHL as Number 3 and better lumber grades. At estimated lumber value, 2x6 and 2x8 SGHL and NHLA grade lumber production as product mix from a log generate higher revenue for all log groups except for the diameter 13" logs. A lower percentage of higher-grade lumber was observed for diameter 13’’ logs than other log groups from this experiment, which resulted in lower revenue.

Production cost of CLTs was determined based on the lumber value to manufacture 40' x 10' plain panels with different combinations by lumber grade of yellow poplar and southern yellow pine lumber alone. Production cost was determined by assuming that lumber value contributes 40% of CLTs' total production cost. The 3- ply CLT panels were manufactured using S. Selects lumber in a major direction, and No 1-grade lumber in the minor direction from YP had a production cost of $662.56 per cubic meter, which cost only $643.10 when SYP lumber was used at referenced lumber value. This study concludes that CLT panels from YP cost 3-7 % more than SYP-CLTs at the referenced lumber values.

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GENERAL AUDIENCE ABSTRACT

This research aims to expand the hardwood lumber consumption in the US by evaluating the opportunity to manufacture cross-laminated timber (CLTs). First, CLT manufacturing industries were visited to know their current capacity to process hardwood lumber. The results suggest that all three CLT industries had sufficient technology to produce hardwood CLTs, and the production was mainly limited by the quality and quantity of lumber available. Commercially hardwood can be used in CLT manufacturing if it can be used for structural application. Hardwood lumber must meet the structural application's minimum requirements to manufacture the structural grade CLTs, so we surveyed the hardwood sawmills to know if they have the required resources to manufacture the structural grade hardwood lumber (SGHL). Only ten percent of the sawmills had required technology to produce SGHL without additional investments. Production of the SGHL also required to generate more revenue for the hardwood sawmills, so we conducted the log yield study to know how the revenue structure of sawmill operation will change from the mixed grade lumber production. At estimated lumber value, 2x6 and 2x8 SGHL and 1-inch National Hardwood Lumber Association (NHLA) grade lumber production as product mix from logs generate higher revenue for all log groups except for the diameter 13" logs. Finally, the production cost of SGHL from the log yield study was evaluated and used to produce CLTs at 40% production cost from lumber at 15% profit margins for sawmills and compare with southern yellow pines CLTs. The results indicate that yellow poplar CLTs cost 3-7 % more than southern yellow pines CLTs at the referenced lumber values. This study concludes that hardwood lumber can be used in CLT manufacturing, so there is an opportunity for hardwood sawmills to expand the market. The first step for commercial production of hardwood CLTs is to produce SGHL on a commercial scale, given that sawmills can benefit from these new products in the current lumber market and meet the minimum requirements of the CLT raw materials.

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LIST OF ABBREVIATIONS

ALSC	American Lumber Standards Committee
ANSI	American National Standard-Standard
APA	The Engineered Wood Association
AWC	American Wood Council
CAGR	Compounded Annual Growth Rate
CLSAB	Canadian Lumber Standards Accreditation Board
CLTs	Cross-Laminated Timber
IBC	International Building Code
ICC	International Code Council
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MSR	Machine Stress Rated
NDS	National Design Specification
NELMA	Northeastern Lumber Manufacturers Association
NHLA	National Hardwood Lumber Association
SGHL	Structural Grade Hardwood Lumber
USFS	United State Forest Service

CHAPTER 1. INTRODUCTION

1 Introduction to the Study

Construction industries around the world are looking for viable and sustainable alternatives to traditionally available construction materials. Because of the increasing cost of construction materials and labor-intensive construction practices, industries are looking for alternatives that reduce onsite work. Prefabrication is identified as a solution to reduce onsite work. However, prefabrication is not always practical with steel and concrete-based construction methods. New construction materials with the advantage of prefabrication must meet or exceed the quality of well-established construction materials. Acceptance of the new materials depends on their strength, safety, and performance during extreme weather conditions and natural disasters. Engineered wood products are emerging as a suitable construction material that includes ease of prefabrication and exhibits the required strength, safety, and performance.

In recent years, engineered wood products have continuously evolved as a new construction material that presents competition to traditionally available construction materials. Mass timber is one of those alternatives, among various engineered wood products, and is a sustainable alternative in the construction market (Espinoza, 2016; Grasser, 2015). Mass timber is defined as large, engineered wood products manufactured with multiple layers of lumber or other wood products to create composite panels by lamination and compression. Mass timber construction has seen significant growth worldwide since the beginning of the 21st century. Beam elements such as glulam were developed in the late 19th century (Smyth, 2018) and continue to be a current construction practice. In the past, post and beam timber frame construction was the only option for mass timber construction. With innovation in wood utilization, panelized wood products have become well established as new mass timber construction materials. With the help of computerized models to aid in the choice of construction materials during design, there has been considerable interest in using mass timber to construct high rise wooden buildings.

There are six different panelized mass timber products available on the market. Nail Laminated Timber (NLT) and Dowel Laminated Timber (DLT) have been on the construction market for centuries. They are still utilized in small or medium-sized construction. When the concept of applying glue to fabricate a panelized wood product was established, then a new era of mass timber products began. As a result, Glued-Laminated Timber (GLT), Cross Laminated Timber (CLTs), Laminated Strand Lumber (LSL), and Laminated Veneer Lumber (LVL) started being fabricated and utilized in building construction. Among various adhesive-bonded panelized wood products, GLTs and CLTs have presented higher strength and stability, prompting significant growth and application of the products. Among all the different mass timber construction options, CLTs have become a widely accepted construction material in recent years (Mohammad et al., 2012; Grasser, 2015) and will be focused in this study.

After almost twenty years since the first production of CLTs in Austria, CLT technology has been growing at the industrial level worldwide. Cross-laminated timbers are produced and consumed in Europe on an industrial scale. However, the production and consumer market has also expanded to Asia, Australia, and North America. Cross-laminated timber, as a construction material, is new to the US construction market. However, it has been receiving more attention from builders and consumers (Grasser, 2015). The CLT construction market in the US has seen continuous growth since 2013, when the first CLT manufacturing facility was established in the US.

Cross-laminated timber was introduced in Europe using a single wood species. Single wood species were initially used to avoid possible design failures related to wood's differing mechanical and strength properties (PRG 320; Grasser, 2015). North American manufacturers can use lumber from multiple softwood species to manufacture CLTs if they have similar mechanical and strength properties. However, PRG 320 excludes lumber from hardwood species to manufacture CLTs for structural applications, although some species have similar softwood lumber properties. Production of structural grade hardwood lumber (SGHL) provides a new opportunity to use hardwood in CLT manufacturing. With the rise in interest in using lumber from different species and the need for an adequate and sustainable supply of raw materials, CLTs from hardwood lumber can be used either with softwood lumber or by itself (Grasser, 2015). This study focused on identifying the opportunities and limitations of using hardwood lumber in CLT manufacturing and measuring hardwood sawmills' current ability to produce SGHL. This study also focused on developing a suitable method of sawing SGHL, evaluating the competitiveness of hardwood lumber as a CLT raw material, and comparing hardwood CLTs economics with softwood CLTs.

1.1 Research Motivation

The minimum requirements identified in PRG 320 for lumber used in CLT manufacturing are "*Lumber grades in the parallel layers of CLTs are required to be at least 1200f-1.2E MSR or visually graded No. 2, and visually graded No. 3 for perpendicular layers.*" This definition excludes the use of hardwood lumber in CLT manufacturing. Specifically, hardwood lumber is not strength graded and manufactured for structural use. Commercial production of hardwood CLTs for construction industries requires detailed assessments of various factors. Five significant issues- growing CLT industries, current status of the lumber production and consumption for both hardwood and softwood, the volume of lower grade lumber produced from hardwood sawmills, lumber value of the lower grade hardwood, and need for additional lumber market for hardwood industries- motivated this research to identify a method to produce structural grade hardwood CLTs on an industrial scale. These factors are discussed in the following paragraphs.

A growing CLT industry significantly adds to the demand for softwood lumber in the domestic market. The US production capacity for softwood lumber is currently insufficient to meet the domestic demand. Approximately 35% of the total consumption of softwood lumber is imported to meet current demands. Thus, finding an alternative to softwood lumber is a potential long-term solution. Hardwood lumber that meets the structural grade quality and is economically competitive to softwood lumber can be a potential supplement to softwood lumber.

At present, hardwood lumber production exceeds the current domestic demand. More than 10% of the lumber produced from domestic sawmills needs an additional market for domestic consumption. Many hardwood forests need timber removal for forest management. However, most sawmills cannot use the lumber due to a minimal market for lower grade logs and lumber. As the volume of low-value lumber increases, hardwood industries struggle to find a sustainable market for their product. Most hardwood lumber, around 54%, is manufactured as industrial-grade lumber (Buehlmann et al., 2017), and it could be manufactured for other markets such as CLT industries which could yield higher revenues for sawmills.

The value of lower-grade lumber from various hardwood species is highly competitive with softwood lumber that can be manufactured for structural application. Thus, potential lower grade logs could be utilized to manufacture SGHL and used as a CLT raw material. CLTs from higher-grade hardwood lumber would be costlier (Grasser, 2015). The higher-grade hardwood lumber value is significantly higher than that of structural-grade softwood lumber, making it economically infeasible. However, lower-grade hardwood lumber could be manufactured to be economically competitive CLTs (Brandner, 2013; Beagley et al., 2014; Grasser, 2015). The potential for using low value hardwood lumber in CLTs presents an incredible opportunity for hardwood market expansion and increases the removal of low-value timber from forest land (Brandner, 2013; Beagley et al., 2014). The results for using low value hardwood lumber as a CLT raw material demonstrates a new market opportunity for the traditional hardwood lumber industry (Beagley et al., 2014). As a result, most of the hardwood sawmills, which are struggling to generate profit and have an increasing volume of low value lumber, could find a new market. This unique market opportunity for low value hardwood lumber would allow for the use of a large percentage of timber in national forests not being harvested due to a lack of high-value markets (Cumbo et al., 2006). Thus, this research is assessing the opportunity to use low value hardwood lumber in CLTs.

1.2 Problem Statements

Hardwood lumber has primarily been used only in customized construction but has been studied as a potential construction material for structural applications. The major limiting factor is the economics of producing structural grade lumber from hardwood species. It is feasible to use low value timber for CLT manufacturing, which can open a new market opportunity for the traditional hardwood lumber industry (Beagley et al. 2014, Mohamadzadeh et al., 2015; Grasser, 2015). With the acceptance of CLTs in engineering construction to build up to 18 story structures, its demand may grow significantly.

As CLTs demand was projected to increase continuously, the gap between production and softwood lumber consumption is widening. The softwood lumber market must find an alternative to reduce imports. One of the potential alternatives is to produce structural grade lumber from hardwood species. There are some difficulties in using hardwood lumber to produce SGHL for CLT use. One of the many barriers is the lack of efficient manufacturing of hardwood lumber, specifically produced to meet CLT standards. Currently, hardwood sawmills are designed for appearance grade lumber production and not for SGHL production (Quesada, 2018; Espinoza et al., 2018).

Another barrier for using hardwood lumber in CLT production is the value of the hardwood lumber. The use of superior grade hardwood lumber to produce CLTs is always higher than softwood lumber for structural use (Grasser, 2015). However, low-value hardwood lumber in the CLT system is a significant opportunity for sustainable markets. Low value hardwood lumber is highly competitive with softwood, and much of it exhibits higher strength properties (Slavid, 2013; Beagley et al., 2014). Hence, low-value hardwood lumber can be a potential alternative to using softwood lumber for CLT production.

Using hardwood lumber in CLTs requires a multi-step approach. The first step is standardizing the manufacturing process to produce uniform dimension lumber that meets the CLT standard. Manufacturing hardwood lumber for the CLT raw material standard requires additional value-added work like drying to 15% and below moisture content, surfacing on all four sides of the lumber, trimming, and ripping to standard width thickness; these processes may increase the production cost of lumber (Adhikari et al., 2020). It is necessary to determine the cost of producing ready to use SGHL and evaluating it for overall competitiveness in CLT construction.

Given differences in manufacturing NHLA grade lumber and SGHL in sawing, drying, surfacing, and grading, sawmills may require adjusting their lumber production process to manufacture SGHL (Denig et al. 1984; Allison, 1987; Ring, 1988). Due to the lack of studies showing the adoption of new processes to produce SGHL, it is hard to understand the required changes in processing, material handling, and associated costs. Also, to manufacture SGHL, hardwood sawmills must see higher revenue. Studies show that producing all hardwood lumber for structural use would not be economically advantageous (Ringe, 1988). It is only economical to saw high-quality lumber for NHLA grades and produce SGHL from the heart center of logs (Allison et al. 1987). Thus, a comparison of mixed lumber production for yield and revenue from mixed grade lumber is crucial to expand the hardwood lumber market. According to Koch et al. (1986), SGHL from hardwood can be economical and practical only if sawmills find an additional market with a potentially higher value, so production to convert lower value lumber to SGHL could be the preferred adjustment in lumber production technology.

Sawing hardwood logs as a product mix of NHLA and structural grade lumber may require adjusting the current production technology in sawmills. Changes in the sawing method may cause changes in supply chain practices and the required labor force, demanding additional investment (Helvoigt et al., 2009). Therefore, another aspect of manufacturing SGHL for CLT use is understanding the current ability of hardwood sawmills to make the necessary changes, where current ability is defined as the capability of sawmills to produce SGHL without acquiring additional resources. Measuring the current ability of sawmills is essential because there are considerable discrepancies in hardwood sawing technology. Most producers process logs based on the needs of the end-users. For sustainable markets, a continuous supply of raw material is essential. To produce an adequate supply of SGHL, sawmills may need to collaborate.

Sawmills could collaborate in production, surfacing, kiln drying, and transportation. Thus, it is necessary to explore how many sawmills are ready for such collaboration. Also, it is critical to know how hardwood CLTs compete economically with softwood CLTs for engineering construction.

Cross-laminated timber is a new construction material in the US. However, use has increased over the last seven years after the first CLT mills were established in the US (Woodworks, 2020). Considering the current status of CLT production and literature reviewed for this research, the problems for hardwood CLTs implementation can be summarized in the following points:

1. CLT mills that processed hardwood lumber to manufacture CLTs had some information on using non-structural grade hardwood lumber for CLT production (Adhikari et al., 2020). Information on industrial and commercial opportunities to use SGHL in CLT mills' existing setups is not well understood. The kinds of adjustments and improvements to CLT mills' existing production setup have not been measured and there is little known to many stakeholders.
2. The percentage of lower grade logs is continuously increasing in sawmill inventories, which increases the volume of low-grade hardwood lumber produced in sawmills. Sawmills are struggling to find a better market for this lumber. One of the opportunities with low value logs is to expand the hardwood lumber market by manufacturing SGHL. Production of SGHL requires adjustments in sawmill operations from lumber sawing to distribution. However, there is little information on existing hardwood sawmills' current ability to produce SGHL specifically as part of a product mix with NHLA grade lumber.
3. The production of all sizes of SGHL is different from producing only 2" x 6" and 2" x 8" SGHL, which is the primary choice of CLT mills. There has been no information on the economic advantages of hardwood sawmill operations to produce only 2" x 6" and 2" x 8" SGHL. Sawmills require detailed information on SGHL production as a product mix to market the product with the appropriate lumber value. However, they lack enough information on the economics of mixed grade lumber production.

4. CLT mills have reported higher production cost of hardwood CLTs using nonstructural grade hardwood lumber rather than softwood lumber (Adhikari et al. 2020). There is no information from the CLT mills on the production cost of CLTs using 2" x 6" and 2" x 8" SGHL and its competitiveness with softwood lumber. How 2" x 6" and 2" x 8" SGHL compares with softwood lumber is crucial in determining hardwood CLTs competitiveness in structural application.

1.3 Research Goals and Objectives

Goals

This study's research goals were to assess the potential to use hardwood lumber in CLT manufacturing and explore the opportunities of using low-value hardwood lumber in CLT manufacturing and its advantages to both hardwood sawmills and CLT manufacturers.

Objectives

The research goals were achieved by addressing four specific objectives. The first objective was to collect CLT manufacturers' perspectives on using hardwood lumber in the current CLT manufacturing process. The first objective also identified the additional value-added work required to use low value hardwood lumber currently available to meet the CLT raw material requirements. This objective was achieved by facility visits and interviews with CLT manufacturers to understand their limitations for using hardwood lumber as CLTs lamella.

The second objective was to determine hardwood sawmills' current ability to produce SGHL from low value logs as a product mix. A study was designed to measure the hardwood sawmills' capabilities based on CLT manufacturers' information regarding the value-added work required to prepare low-value hardwood lumber. A survey of hardwood lumber producers in the US was conducted to observe the potential and the barriers that manufacturers foresaw regarding entering the CLT market and their current ability to produce structural lumber from low value hardwood lumber as CLT raw materials.

The third objective was to conduct a new product mix's economic feasibility as a CLT raw material from yellow poplar (YP) logs. A log yield study to compare the National Hardwood Lumber Association (NHLA) and SGHL for visual grading was developed. Two different lumber grading rules were used to compare the yield between existing lumber production and proposed mixed grade production: NHLA rules for grading high-value lumber and Northeastern Lumber Manufacturers Association (NELMA) grading rules for SGHL. The existing sawing practices were used to produce higher-grade lumber from the logs' outer zones, as described by Allison et al. (1987). The cants were processed to produce 6" and 8" width SGHL to meet the PRG 320 requirements.

The fourth objective was to evaluate the economics of producing CLTs manufactured using SGHL, considering the log yield study results from Objective 3. Currently, structural grade hardwood CLTs are not produced in the US. The production cost of NHLA grade lumber from the low-value YP logs from the log yield study was used to determine the lumber value of SGHL. Production of CLTs using SGHL was studied to measure the economic opportunity of hardwood CLTs. The lumber value contributes around 50% of the CLT panel's total production cost (Espinoza, 2016).

Thus, the specific objectives of this research were:

- Objective 1: Find the current opportunities and limitations of utilizing hardwood lumber as a CLT raw material from the CLT manufacturer's perspective.
- Objective 2: Measure the current capabilities and limitations of hardwood sawmills to produce SGHL for CLT use as a product mix.
- Objective 3: Measure the economic feasibility of producing SGHL with NHLA grade lumber from yellow poplar logs.
- Objective 4: Determine the CLT production cost from SGHL produced from yellow poplar lumber and SYP and compare the production cost per unit volume.

1.4 Research Questions

One of the significant barriers to produce hardwood CLTs commercially is the efficient manufacturing of hardwood lumber to meet the minimum CLT production specifications (Grasser, 2015). Traditionally, hardwood sawmills were designed for appearance grade lumber production, not for the specific structural grade purpose required by PRG 320. Promoting hardwood sawmills to manufacture structural grade hardwood CLTs in industrial production requires assessing the CLT mills and hardwood sawmills' current technology. Additionally, developing a cost-effective sawing method to produce SGHL that improves the sawmill's financial status is needed. Thus, the research question for this study is:

What is the potential of using low value hardwood lumber as CLT raw material on an industrial scale?

To answer the primary research question, this research answers the following sub-questions.

1. What are the manufacturers' perspectives on using hardwood lumber in CLT manufacturing?
2. What is the current ability of hardwood sawmills to produce structural grade hardwood lumber?
3. What are the yield and economics of producing structural grade hardwood lumber?
4. What is the economic competitiveness of hardwood and softwood CLTs?

1.5 Research Hypothesis

Four different hypotheses were tested to complete this research. These hypotheses were postulated according to the framework developed to carry out the research:

H1: Cross laminated timber manufacturers are ready to use hardwood lumber for commercial production.

H2: Hardwood sawmills in the United States are ready to produce structural grade lumber.

H3: Mixed grade lumber production from hardwood species to produce structural grade hardwood lumber with National Hardwood Lumber Associations grades will yield higher recoveries to sawmills.

H4: Cross laminated timber from structural grade hardwood lumber can compete with softwood cross laminated timber made with softwood lumber.

1.6 Overview of the Research Methodology

The study was designed in four stages. The overview of the study design is shown in Figure 1-1. Information regarding CLT manufacturing opportunities and limitations for hardwood lumber was observed through facility visits, followed by in-person interviews with CLT manufacturers. The focus of the interview was to obtain information on fundamental problems with lumber acquisition and its impact on the overall product quality and cost.

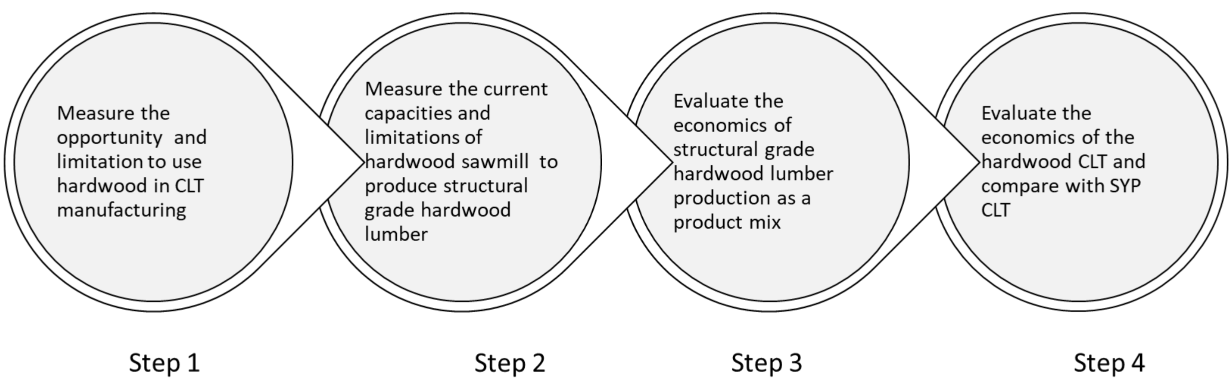

Figure 1-1: The overall study design to complete the research

Hardwood is not the standard lumber choice in current CLT manufacturing practice. However, the basic setup for CLT manufacturing from hardwood lumber is similar to softwood, so multiple questionnaires were designed to understand the potential to use hardwood lumber at the current CLT mills setup. Possibilities and limitations were studied by identifying the required value-added work to use hardwood lumber currently available in the market.

In the second stage, with results from the CLT manufacturer's perspectives for using hardwood in CLTs from objective 1, a list of value-added work required to produce ready to use SGHL was developed. These requirements were analyzed to develop survey questionaries to study sawmills' current ability and limitations to produce SGHL. The primary objective was to determine the feasibility of supplying finished (requiring no additional value-added work) SGHL to the CLT manufacturers. The mills' responses were studied on four levels: sawmill type and sawmill size, the volume percentage of 2 common and lower-grade lumber, and the average production cost of 1000 bf of lumber. All the sawmills' responses were utilized to obtain each company's current ability and defined as the readiness index (RI). The company's RI measured their current capability of producing SGHL without an additional investment of resources.

In the third stage, the economics of producing SGHL as a production mix along with NHLA lumber from the hardwood logs was studied through a log yield study. Logs were sawn to produce higher grade NHLA lumber from high-quality zones and converted potentially lower-grade lumber to SGHL. NELMA rules were applied to grade SGHL. The observed outcomes were compared for yield and revenue from samples of yellow poplar logs. The yield and revenue of producing NHLA only and mixed grade (NHLA+NELMA) lumber outputs were compared and used to determine the production cost of the SGHL.

In the fourth stage, the production cost of hardwood CLTs using the SGHL produced from YP logs was determined. Production costs based on different lumber values in the major and minor direction for a different combination of the CLTs were evaluated.

1.7 Research Limitations

Every research project must make compromises in study design, and those constraints were a significant component of the research. No research is completed in a perfect environment (Connelly, 2013). There are multiple limitations to this research. The research was designed to evaluate hardwood CLT's potential and have it completed in four steps to address specific research objectives. There were some compromises in the data collection methods and access to information which are addressed by the respective objectives in the following paragraphs.

Hardwood lumber use in CLTs is not a common practice. Most of the hardwood CLTs manufactured are for study purposes or experimental samples. Only a few projects have been completed so far. Thus, there is scant literature available on hardwood CLTs and the associated production costs. Due to limited resources, it was not easy to collect relevant information to establish a legitimate conclusion without some assumptions and considerations.

Additionally, the number of CLT producers in North America is limited. Only six companies had obtained the APA accredited license to produce CLTs at the time of the study. The sample size for the interview survey was small, as only three sawmills agreed to be interviewed and allowed field visits. Manufacturers have adopted technology to use softwood lumber in their production setup. Only two manufacturers considered using hardwood lumber as raw material to manufacture non-structural CLTs. None of them had experience producing hardwood CLTs for engineering applications. There are different technologies for manufacturing CLTs, and the technology adopted by the two companies is unique to itself. The concept of hardwood lumber in CLTs is not well known on an industrial scale. During the interview process, industries did not answer some questions citing company policies, so the results excluded their practices. Many responses collected from CLT mills were based on respondent knowledge, not from field experience. Therefore, results from the interview surveys and field visits were the summary of the participating companies' experience and knowledge and limited to the technology adopted by these companies.

The current ability of hardwood sawmills to produce SGHL for CLT uses was studied using a survey. The survey was completed using two different data collection tools: paper and online surveys. There are numerous but very small-sized hardwood lumber producers in the Appalachian region. Many sawmills only saw certain types of logs, limited to their markets. For a survey study, the limitations and strengths are the response rate. For this study, the response rate was a significant limitation. The response rate was approximately 6%. The low response rate limited the ability to generalize from the responses. One of the reasons for a low response rate was sawmill size and practice. Many sawmills produced lumber for the local market and had no interest in expanding beyond this. The market discussed for SGHL in the survey does not exist as PRG 320 does not accept hardwood lumber for CLTs' engineering use. Additionally, SGHL production may demand additional investment to adjust sawmill technology. At present, there is no guarantee of this potential market. So, some sawmills expressed no interest in the potential new product or this survey.

The log yield study required resources and time from the sawmills, so very few sawmills came forward to help. Multiple species of the hardwood logs can be manufactured as SGHL. However, this research chose to use only yellow poplar logs of specific grade and dimension. Wood has a higher variation on lumber yield based on log grade, allowable defects, and log dimension. To draw a general conclusion, the sample size for the experiment should be large. The log yield study was completed sawing only 126 logs of 12-feet length and a small end diameter of 12" to 15". All of these logs were of F3 grade quality graded under USFS log grading rules. This sample size excluded all other dimensions and grades of the log. The standard thickness of the 2" x6" and 2" x8" lumber used in CLT production is 1.5 inches. However, this study used 2" thick lumber for the main study, so the log yield to produce standard thickness lumber is different from the observed yield. The revenue was evaluated based on the grade of green and rough lumber, which is not the standard practice because lumber is graded after completing all the other value-added work. Therefore, the log yield by grade may be different from what is reported by this study. The revenue estimate from this study used current lumber values for both hardwood lumber and softwood lumber. At present, the structural grade lumber value has spiked to record highs for softwood lumber due to a shortage caused by a global pandemic, so the actual revenue in a regular market may be different.

The CLT production cost depends on many variables, from raw material acquisition to dispatch of the product. The variable cost depends on the manufacturing technology adopted by the industry. Being a customized product for engineering applications, the CLT's production cost for each panel differs from other panels from the same batch. This study's objective was to determine the production cost of the SGHL based on a log yield study and to observe the production cost of CLTs based on lumber value. The production cost of the SGHL was determined by the same method as NHLA grade lumber for green and rough lumber. NELMA grading and dressing costs for lumber were added to the estimated lumber cost based on the participating agencies' information which can be different for other sawmills. The CLT production cost was generalized based on the lumber value as the percentage of the total production cost from lumber value, so this study did not consider the changes in other cost factors.

1.8 Contributions of the Research

This study is significant for understanding the status of CLT production and adopted technologies in the US. This study is also helpful for understanding the potential opportunity for hardwood sawmills to expand its lumber market. The outcomes of this research are discussed according to research objectives.

The first objective was to identify the current limitations of utilizing hardwood lumber as a CLT raw material from the CLT manufacturer's perspective. The observed outcomes of this objective included information on:

- The technologies adopted by US-based CLT mills
- The limitation of existing CLT manufacturing technology in the US
- The quality of raw material received by the CLT mills
- Opportunity to use hardwood lumber in CLTs manufacture
- Collaborating with hardwood sawmills and CLT mills to obtain the quality raw material

This research's second objective was to measure the hardwood sawmill operations' current capabilities and limitations to produce CLT raw material from low value hardwood lumber as a product mix. The observed outcomes of this objective include:

- Demographic information of the hardwood sawmills
- A measure of the current capacity and limitations of sawmills to produce SGHL
- Sawmills' willingness to produce SGHL as a product mix
- Sawmills' willingness to collaborate with other stakeholders
- Expected demand and revenue for SGHL production as product mix
- The measure of the resources required by sawmills to begin SGHL production
- Overall ability of hardwood sawmills to produce SGHL to meet the CLT standard

Measuring a new product mix's economic feasibility as a CLT raw material from YP logs yielded some specific information. The observed outcome of this objective includes:

- Applicability of mixed grade lumber production as product mix in current sawmill operations
- Percentage of lumber yield in NHLA grading
- Percentage of lumber yield from mixed grading (NHLA +NELMA)
- Change in lumber volume by grade from producing SGHL as product mix.
- Information on yield suppression or improvements from combined grading practice
    - Economics of the NHLA grading and mixed grading
    - Identification of value-added processes to produce SGHL as CLTs lamella and the cost to convert SGHL to CLT raw materials and potential lumber value of SGHL

Objective 4 was to determine the economic opportunity of CLTs lamella manufactured from SGHL from YP. The observed outcomes of this objective include:

- The economic comparison of SYP and YP lumber lamella and the production cost of CLTs from SYP and YP
- A comparison of the manufacturing cost of YP and SYP CLTs at the different cost percentages of the lumber

CHAPTER 2 LITERATURE REVIEW

2 Introduction to CLTs

Cross Laminated Timbers (CLTs) are wood panels comprised of several lumber layers with boards stacked crosswise at 90-degree angles. Lumber used in CLTs should be kiln-dried to a moisture content of 12±3% at manufacturing (ANSI/APA, 2017). Glue, nails, or wooden dowels are used to fasten the CLT lamella. An odd number of layers, three to seven layers per panel, is common practice to fabricate CLTs (ANSI/APA, 2017). Some of the companies in Europe are manufacturing up to nine layers. The thickness of individual lumber must be 5/8" to 2". The common lumber choice is 2.4" to 9.5" in width. Cross-laminated timber layers parallel to the outside layer must be a minimum of visually graded Number 2 softwood and visually graded Number 3 softwood for the perpendicular layers (ANSI/APA, 2017).

Brandner (2013) defines CLTs as the engineered building material from wood that offers engineers and architects the potential to achieve timber structures at higher levels. In the past, mid-rise and high-rise buildings were limited to mineral-based construction materials such as reinforced concrete, brick, and steel. However, the introduction of CLTs has provided an additional choice. CLTs are promoted as a fabricated system and recognized as CLTs systems in construction rather than plain CLT panels (KLH, 2019). The CLT system includes the fabricated or non-fabricated CLT panels, required joinery and fitting parts, and necessary ancillaries, with assembly guidelines and set up for logistics and shipping (Grasser, 2015; KLH, 2019). For this study, CLTs are discussed as a CLT system.

The sustainable nature of wood due to carbon sequestration (Bolduc, 2017), efficient and quicker construction time, excellent seismic performance, appropriate insulation properties, and minimum embodied energy are among CLT's advantages compared to concrete construction (Quesada, 2018; KHL, 2019). Beagley et al. (2014) described CLTs as a construction material that provides reduced onsite work, as the CLT panels are prefabricated in the desired dimensions before they are transported to the worksite. Prefabrication ultimately minimizes the use of heavy equipment on the job site and significantly increases work efficiency. Grasser (2015) and Espinoza (2016) concluded that CLTs in construction sites do not add more cost since panels are prefabricated, and lighter structures from CLTs require less foundation work.

Cross-laminated timber is an eco-friendly construction material (Beagley et al., 2014; Grasser, 2015), and it relates directly to accumulating CO_2 during timber growth and embodying it in the structure for years. Cross-laminated timber in a structure can store a massive volume of carbon components. These carbon components are released into the environment as CO_2 and other global warming gases when consumed in ways other than building structures. In the long run, increasing lumber production to meet lumber demand leads to grow more forests (Brandner, 2013) and ultimately helps in carbon sequestration (Bolduc, 2017).

Among wood composites, CLT's strength-to-weight relationship provides a solution to the ongoing concern of using wood in mid to high-rise buildings as an alternative to steel and concrete (Mohammad et al., 2012). With the CLT, timber buildings can be built up to 30 stories (Green et al., 2012). The tallest wooden building constructed in North America using CLTs is Brock Commons Phase-1, 53m (Hilburg, 2017). The largest CLT building constructed is in London, a 10-story, a 121-unit residential building built almost entirely with a CLT system (DeHart, 2017).

CLTs have not been used much in the first decade of the 21st century. This trend has been shifting in modern construction over the last seven years. CLTs offer numerous advantages over other construction materials. Some of the benefits listed by researchers such as Brandner (2013), Grasser (2015), and Buehlmann et al. (2017) include, but are not limited to:

- Ease of factory prefabrication of the parts and design flexibility
- Reduced onsite work and assembly as a preferred construction technique
- Outstanding structural stability and stiffness
- Higher load-bearing capacity against in-plain and out-of-plain stresses

- Ease of transferring the load into two-structural directions
- Higher seismic and fire resistance ability
- Substantially reduced foundation work for construction

Adhesive-bonded CLT production, using glue to the laminate lamella, is the widely accepted production practice. In addition to this, some companies use Beech dowels, screws, or aluminum nails to fasten the CLT lamella (Espinoza et al., 2016). CLT panels can be categorized based on laminating practice in three different types: glue-laminated, nail laminated, and dowel laminated. Adhesive bonded CLTs makes up 95% of the market (Plackner, 2014).

Table 2-1:CLTs grade and specification details

CLTs Grade	Specification details.
E1	1950f-1.7E Machine Strength Rated (MSR) Spruce-Pine-Fir (SPF) in all parallel layer and No. 3 SPF in all perpendicular layer
E2	1650f-1.5E MSR Douglas Fir-Larch lumber in all parallel layer and No. 3 Douglas Fir-Larch lumber in all perpendicular layer
E3	1200f-12E MSR, Northern Species, Eastern Softwoods or Western Woods in all parallel layers and No. 3, Northern Species, Eastern Softwoods or Western Woods all perpendicular layers
E4	All Parallel layers: 1950f -1.7E MSR Southern pine lumber and All Perpendicular layers: No. 3 Southern pine lumber
E5	All Parallel layers: 1950f -1.7E MSR Hem-fir lumber and All Perpendicular layers: No. 3 Hem-fir lumber
V1	All Parallel layers: No. 2 Douglas fir-Larch and All Perpendicular layers: No. 3 Douglas fir-Larch lumber
V1(N)	All Parallel layers: No. 2 Douglas fir-Larch (North) and All Perpendicular layers: No. 3 Douglas fir-Larch lumber (North)
V2	All Parallel layers: No. 1/No. 2 SPF lumber and All Perpendicular layers: No. 3 SPF lumber
V3	All Parallel layers: No. 2 Southern pine lumber and All Perpendicular layers: No. 3 Southern pine lumber
V4	All Parallel layers: No. 2 SPF lumber and All Perpendicular layers: No. 3 SPF lumber
V5	All Parallel layers: No. 2 Hem-fir lumber and All Perpendicular layers: No. 3 Hem-fir lumber
S1	2250 f-1.5E Laminated Veneer Lumber in all layers
S2	2251 f-1.5E Laminated Strand Lumber in all layers
S3	2252 f-1.5E Oriented Strand Lumber in all layers

Another method to differentiate CLTs is by grade. The lumber quality used to fabricate the CLT is the basis for industrial CLT grading. There are fourteen different CLT categories based on lumber species used and the grading practice defined by PRG 320. If the lumber used in CLT production is machine graded, CLTs fabricated using this lumber are classified as E-rated. If visually graded lumber is used to manufacture the CLT, they are categorized as V-rated, and if strand lumber is used instead of lumber, those CLTs are classified as S-rated. The details of the CLT grades and lumber types used in a different grade, as described in PRG 320, 2019 handbook, are shown in Table 2-1.

2.1 History of CLT manufacturing

Europe is a pioneer in CLT manufacturing technology, as well as CLTs building systems. At the beginning of the 1990s, the first fabrication of CLTs was started in Europe's Alpine region (Grasser,2015). Although Walsh et al. (1923) had registered a similar product as composite lumber from Washington state in the US, it was not developed as a construction material until many years later. However, CLTs' industrial production began in 1996 in Austria and Germany (KLH, 2019). In 1996, industry and academia worked together to develop a sideboard from sawmilling, which resulted in modern CLTs (Crespell et al., 2011; Brandner, 2013). The commercialization of CLTs in the construction market began after successfully implementing the manufacturing standard and production procedure.

In 1998, two industries in Europe received formal national product authorization and became the first certified CLT manufacturers (Crespell et al., 2011; Brandner, 2013). After that, numerous other producers received certification and started manufacturing (Brandner, 2013). A milestone in CLTs development was the first European Technical Approval (ETA) for CLT systems in 2006 and the European CLTs Standard development in 2008 (Schickhofer, 2013). European experience and expertise are the benchmarks for the new CLTs markets. For the last ten years, many countries across the globe have accepted construction using the CLT system. Currently, Australia, Japan, North America, and New Zealand have multiple CLT manufacturing facilities.

2.1.1 **The European CLTs Industry**

Currently, Europe is leading in manufacturing CLTs on an industrial scale. CLTs' capacity and production output in Europe have increased exponentially following the European CLTs Standard development in 2008 (Espinoza et al., 2016; Grasser, 2015). A significant influence in CLT's promotion was the green building movement, which initiated changes in European building codes, promotional efforts, and sustainable supply chain practices (Crespell et al., 2011; Thiel, 2014). The momentum of green construction and the opportunity with CLTs as an alternative to mineral-based construction material helped industrialize CLT in Europe. The growth was solidified by the European standard for CLT manufacturing implemented in 2015 (Pahkasalo et al., 2014).

In recent years, annual CLT production has shown remarkable growth in Europe. In 2015, 80% of global CLT production was in Europe, where Austria produced 60% of the total European CLTs (UNECE, 2016). In 2016, the estimated CLT production in Europe was 290 million board feet (bf). CLTs' production volume was predicted to increase to about 530 million bf by 2020 (UNECE, 2016, Plackner 2015). With the increasing interest in the CLT market and the world's investment trends, CLT's projected total production will be approximately 1.3 billion bf by 2025 (Plackner 2015). In countries like Austria, Switzerland, Germany, and the Czech Republic, manufacturing volume tripled from 2008 to 2016 to 288 million bf (Ebner, 2017).

In recent years, the CLT production and consumption rate have continued to increase, as is seen by the 35% increase in production volume from 213 million bf in 2014 to 288 million bf in 2016 (Ebner, 2017). The increase in European CLT production after 2011 was due to the automation, upgrades, and modernization of the existing production facilities (Plackner, 2014). The United Kingdom, Germany, Switzerland, Austria, and Italy are all significant European CLTs customers, which adds up to 70% of Europe's total CLT use (UNECE, 2016). With continuous production and consumption growth, the CLT construction system has a promising future (UNECF, 2016). Pahkasalo et al. (2014) estimated that CLTs sales growth was expected to increase by no less than 10% each year in European markets. This increase is attributed to consumers' and builder’s awareness of CLTs' use.

2.1.2 CLTs Status in North America

Cross-laminated timber manufacturing in North America is growing. Production of CLT panels for the structural market was projected to grow at a compounded annual growth rate (CAGR) of 16.2% starting in 2017, with a $1.833 billion market value by 2024 (Energias, 2018). Energias (2018) also estimated that the North American region would have the highest CAGR in the following seven years, starting in 2017. The Beck-Group (2018) estimated that the US's CLT production capacity in 2020 would reach approximately 257,700 m^3 if all of the CLT manufacturing facilities were to run at their full capacity. The Beck-Group (2018) stated that fabricating CLTs to meet 2020 demand would require about 1.95 billion bf of lumber. They also estimated the structural grade of CLTs' demand would be 515,400 m^3 by 2025, which would require approximately 3.9 billion bf of nominal size lumber.

Demand for CLT in the US and Canada is mostly driven by architects and engineers interested in wood-based innovative construction products and building systems (Mohammad et al., 2012). By including CLTs in the building code, North America has positively impacted CLT manufacturing. Recently, the International Building Code (IBC) has approved the construction of up to 18 story buildings using the CLT system. This approval has created positive momentum toward accepting the CLT as an alternative construction material for mid-and high-rise structures.

Currently, there are seven CLTs producers in North America (APA, 2020). Two companies are in Canada, and four manufacturers are operating in the US. All the companies are CLTs certified members of The Engineered Wood Association, aka APA (APA, 2019), except Sterling, which manufactures CLT panels for matting (Sterling, 2019). Structuralam, Nordic, and the D.R. Johnson are the first North American CLT manufacturers to obtain the APA certification to meet PRG 320 (Pei. et al. 2016).

Another CLT manufacturers, SmartLam from Columbia Falls, Montana, was the first U.S.-based CLT manufacturer that initially produced industrial CLTs matting. In response to increased demand and acceptance of CLTs for building applications, SmartLam completed the APA certification for CLT manufacturing in August 2016 (SmartLam, 2019). Now seven industries have received APA certification to produce CLTs for engineering use. The latest CLT manufacturers to receive APA certifications are Vaagen Timber LLC and Freres Lumber Co., LLC.

The US's CLT market is vastly different from Europe (Pei. et al. 2016). In Europe, CLTs are mostly used to construct residential buildings. However, in the US, residential housing is built using well-developed timber frame construction systems (Grasser, 2015). Until there are other sustainable alternatives, timber frame construction will remain the primary choice. CLTs are suitable substitutes for timber frame construction and are accepted by many architects, designers, and builders. Commercial buildings, large and medium-sized public buildings, industrial buildings, and multi-purpose, high-rise wooden structures are considering using the CLT system (Pahkasalo et al., 2014). With the success of public and commercial buildings, CLTs are expected to develop customer confidence. Customer awareness of mass timber construction will help to open doors for CLT systems in single family housing. Opportunities to use the CLT system to construct single family housing will be the economic turning point for establishing the CLT system as a sustainable construction material in North America.

The first CLT project constructed in North America was in British Columbia, Canada, and was built to LEED Gold status. The six-story tall building was built as a wood hybrid building using wide-ranging engineered wood products. This building was primarily completed using glulam and CLT components (Mah, 2014). In 2017, the CLT system was used to build Brock Commons Phase-1, a student residence building at the University of British Columbia. This 18-story building with a height of 53m is the tallest wooden structure globally, surpassing the 32m-high apartment building in Melbourne, Australia, and Carbon 12 in Portland, Oregon, US (Espinoza et al., 2016; Hilburg, 2017; UBC, 2018). In recent years, CLT manufacturers have been aggressively advancing technology to build high-rise buildings in North America.

Cross-laminated timber manufacturers in the US are still promoting the CLT system and are continuously increasing the production volume from softwood lumber. SmartLam increased its capacity to produce more than one million bf of CLTs per month from its Montana plant (Forth, 2018). Also, the company acquired International Beams from Alabama in 2019 to expand its market reach. D.R. Johnson is producing CLTs to meet the West Coast's demand. The company has constructed a new building at the College of Forestry at Oregon State University, using more than one million bf of CLT panels, glulam beams, and columns (D.R. Johnson, 2019). New CLT plants are expected to open on the US's east coast, so established companies can expand their production with new factories in different locations (EESI, 2018).

2.1.3 CLT Manufacturing Beyond Europe and North America

In addition to Europe and North America, CLT's development has expanded to Asia and the Australian continent. Since early 2017 in Australia, "Green," "XLam Australia," and "Crosslam" have been manufacturing commercial CLT systems (Green, 2019; XLam, 2019; Crosslam, 2019). Also, CLTs system development and promotion have been growing in New Zealand (Plackner, 2015b). Commercial CLT production in New Zealand began in 2012 in a facility built in 2010 (XLam, 2019).

Japan is leading the Asian region in CLT manufacturing and improving European technology with advanced automation. In 2014, the Japanese government proclaimed an action plan with three objectives to encourage the country's CLT industry (Plackner, 2015d). These action plans included: preparation of building regulations, a collection of case studies to understand the strengths and weaknesses of the existing technology and products, and the development of a CLT production chain. As a sustainable plan to promote CLTs, the Japanese Ministry of Agriculture and Forestry subsidized and promoted eight CLTs projects. In response to this government initiative, three new CLT production facilities were launched in Japan. They completed 21 CLT projects by the end of 2016 (Muszyński et al., 2017). Japan's annual CLTs system production in 2016 was approximately 21.2 million bf, and the projected CLT production in Japan for 2024 is 210 million bf (Muszynski et al., 2017; UNECE, 2016). In response to a higher appreciation of CLTs globally, India and China have also initiated CLT manufacturing facilities in their countries. China has already built a pilot CLT plant to begin industrial production. The following section will discuss more on CLTs in North America and its acceptance in the construction market.

2.2 North American Building Codes and CLTs Standard

In the US, the International Building Code (IBC) limits wooden buildings to four stories (Cain, 2014). To expedite CLT uses in North America's building practices, these construction materials must be recognized by North America's regulatory systems (Grasser, 2015). North America is aggressively working to standardize CLT products. To adopt CLTs as a standard building material, North America developed a multi-level strategy. The first level of the strategy was to develop a CLT product standard, followed by the second level, a material design standard. The third level was to develop an effective plan for the adoption of the standards in the building codes (Mohammad et al., 2012).

The first phase of developing a CLT standard for construction material was completed in 2012. In 2012, APA/ANSI PRG 320 - American National Standard for Performance-Rated Cross-Laminated Timber was published (Grasser, 2015). This published standard is the only standard guideline for CLT production in the US and Canada. It was updated in 2015, 2017, and 2019. The second level, the material design level, was completed in the US and Canada in 2015. In 2014, the Canadian Wood Council (CWC) had included CLTs guidelines in the Canadian Standard Association -086 (CSA086). CWC included CLT guidelines under Engineered Design of Wood Standard. In 2015, the US also included CLTs in the National Design Specification for Wood Construction (NDS) by the American Wood Council (AWC).

The third level of CLTs implementation was CLT's adoption in Canada's building codes -NBCC and the US-IBC. The adoption of CLT's in the US began by referencing the PRG 320 in the 2015 edition of the

NDS for Wood Construction (Pei. et al. 2016). Full design provisions related to CLTs were implemented in 2016 as a supplement to the 2014 CSA086 in Canada (Pei. et al., 2016) to increase CLTs adoption. In the US, the NDS referenced ANSI/APA PRG 320- 2017 and updated the CLT deflection provision to include the CLT section's sufficient shear stiffness. Under the current building code, builders must get certification locally to construct wooden structures more than four stories high (Cain, 2014; Grasser, 2015).

2.2.1 CLTs Standard in North America

In North America, Canada was the first to standardize the CLT production process and product. Canada's FPInnovations researched the CLT market's scope and published the CLT Handbook in 2010. The US also published a handbook on CLT manufacturing in 2013. There have been limited CLTs markets in North America due to a lack of awareness and knowledge about using CLTs as a construction material. Thus, Canada and the US worked together to develop a North American standard for CLT products in 2011. This standard is the American National Standard-Standard for Performance-Rated Cross-Laminated Timber (ANSI/ APA PRG 320), hereafter referred to as PRG 320. In 2015, PRG 320 was updated to match the International Building Code (IBC) 2015 requirements (ICC, 2015). In 2015, 2017, and 2019, the PRG 320 standard document was updated with additional information on test procedures and added various lumber species and CLTs' grades to widen the use.

As documented in the PRG 320-2012, CLTs lumber can only be made from softwood species. These softwood species must be qualified by the American Lumber Standards Committee (ALSC) under PS 20 or the Canadian Lumber Standards Accreditation Board (CLSAB). Additionally, only softwood lumber from species with a specific gravity greater than 0.35 can produce CLT panels (PRG 320). In CLT manufacturing, lumber used in the parallel direction must be designed as the primary strength direction. The minimum specification should be visual grade Number 2 or 1200f-12E for machine-graded lumber under the machine stress rated (MSR) grading system for lumber being used in the parallel layers of the CLT (PRG 320). For lumber used in the parallel direction, the minimum lamination width should be 1.75

times the thickness. The minimum lumber dimension used in CLTs will be 2X3 inches (PRG 320). In the perpendicular layers of the CLT, visually graded Number 3 lumber is the minimum requirement. The lumber's width should be more than 3.5 times the lumber's thickness to avoid failure due to interlaminar shear force and creep (PRG 320). Thus, the minimum lumber dimension should be 2 x 6 for use in the perpendicular direction. The same species or species combination is suggested for the same layer to avoid mechanical and physical properties. However, an adjacent layer can use different species or species combinations under PRG 320. Moisture content is the primary concern for the structural use of the lumber. Lumber should not exceed a moisture content of 12±3% during CLTs production to avoid structural performance failure due to delamination (PRG 320).

2.2.2 **Requirements of PRG 320**

In North America, CLT mills only qualify to produce CLTs for structural applications after obtaining the certification proposed by PRG 320. The qualification is granted by an approved agency such as the APA – The Engineered Wood Association. The standard document was updated in 2015, 2017, and 2019. The minimum requirements of the CLT standards in North America are discussed in the following sections.

2.2.3 **Component Requirements**

Cross-laminated timber has two primary components, laminations, and adhesives, used for finger-jointing and face bonding (PRG 320). Lumber from softwood species, with a minimum specific gravity of 0.35, is accepted under PS 20 by the ASCL or under CLSAB it can be used to manufacture CLTs. This lumber should meet a minimum of visual grade Number 2 or 1200f-1.2E for parallel layers if machine graded. For the perpendicular layers, the lumber should be of a visual grade Number 3. In a single layer, the manufacturer can use the same lumber species or other species combinations with similar properties. However, lumber in different layers can be from different species, provided it meets the minimum requirements of the lumber for a given layer. Table 2-2 summarizes the requirements for the CLT components, according to PRG 320.

Table 2-2: Requirements for CLT components

	CLTs components and measures	*Required Standards*
Lumber		
	Lumber species	Only softwood lumber species Minimum specific gravity of 0.35. Species must be recognized under ALSC under PS 20 in the US. Species must be recognized under CLSAB under CSA O141 in Canada.
	Lumber grades	For parallel layer Minimum of MSR 1200f-1.2E Minimum of visual grade Number 2 For perpendicular layer Minimum of visual grade Number 3
	Lamination sizes	The thickness of the lamella should be between 16 to 51 mm The width of the lamella in major strength (parallel) direction should not be less than 1.75 times the thickness of the lamella The lamella's width in minor strength (perpendicular) direction should be greater than 3.5 times the thickness. If the width must use less than mentioned above, it should be evaluated according to ASTM D6815
	Moisture content	Must be less than 15% at the time of manufacturing
Adhesive		
		In the US Must match AITC 405 standard requirement except section 2.1.6 on heat performance, which should meet the DOC PS1 section 6.1.3.4 standard. In Canada Must match the specifications of CSA O112.10 standard and heat performance requirements as per DOC PS1 section 6.1.3.4 standard. Additionally, it should match the AITC 405 section 2.1.3 and 3.3 requirements
Joints		
	Face bonding surface	All surfaces should be dressed before manufacturing and should be free of deviation. Allowable thickness across the width should be between ± 2 mm, and lengthwise variation should be between ± 3 mm
	Finger-joint strength, wood failure, and durability	In the US Match the requirements of ANSI/AITC A 190.1 section 5.5.1 and 5.5.2 Match the requirements of ANSI/AITC A 190.1 section 4.5.4.2, 4.5.4.3 and 5.5.1.3 In Canada Match the requirements of CSA O177 section 9.5
	Face- and edge-joints Wood failure and durability	In the US Match the requirements of ANSI/AITC A 190.1 section 4.5.4.1, 4.5.4.3 and 5.5.2 Match the requirements of ANSI/AITC A 190.1 section 4.5.4.1, 4.5.4.3 except shear strength In Canada Match the requirements of CSA O177 section 9.2 and 9.3 except shear strength

Moisture content is of the utmost importance. The moisture content for each lumber piece should be less than 15% at the time of bonding. Phenol resorcinol formaldehyde, emulsion polymer isocyanates, and polyurethane are the adhesives used in CLT manufacturing (Yeh et al., 2013).

2.2.4 Structural Performance Requirements

The North American CLTs standard does not specify the dimensions (sizing, width, or length) of CLT panels under the PRG 320 standard. Cross-laminated timber panels are produced with a width between 0.6 to 3 m and up to 18 m lengths (Grasser, 2015). Some manufacturers in Europe have fabricated large-scale CLT elements of 5.5 m X 30 m. However, such dimensions are uncommon in the US (APA, 2018). According to the PRG 320 standard, CLT panels' maximum thickness can be 20 inches. The details of the CLT structural and structural performance requirements, according to the PRG 320, are listed in Table 2-3.

Table 2-3:CLTs minimum structural performance requirements

Component	*Elements*
Dimension	Panel thickness: ± 1.6 mm Panel width: ± 3.2 mm Panel length: ±6.4 mm
Straightness	Maximum of 1.6 mm
Structural performance	Each CLTs component should be evaluated according to Table 1 of ANSI/APA PRG 320 standard.

2.3 CLT Manufacturing Process

Production of CLTs in North America is standardized under the guideline of PRG 320 published by APA. PRG 320 is known as the "Standard for Performance-Rated Cross-Laminated-Timber," which is the only standard guideline for CLT manufacturing and specification in North America. The PRG 320 standard regulates CLTs' raw materials minimum specification, the manufacturing process, and final product specifications in North America. The ANSI accepted the standard set by PRG 320. At present, seven CLT manufacturers are APA certified. The CLT system's overall production line can be generalized, despite the different technology accepted by manufacturing companies, as shown in Figure 2-1.

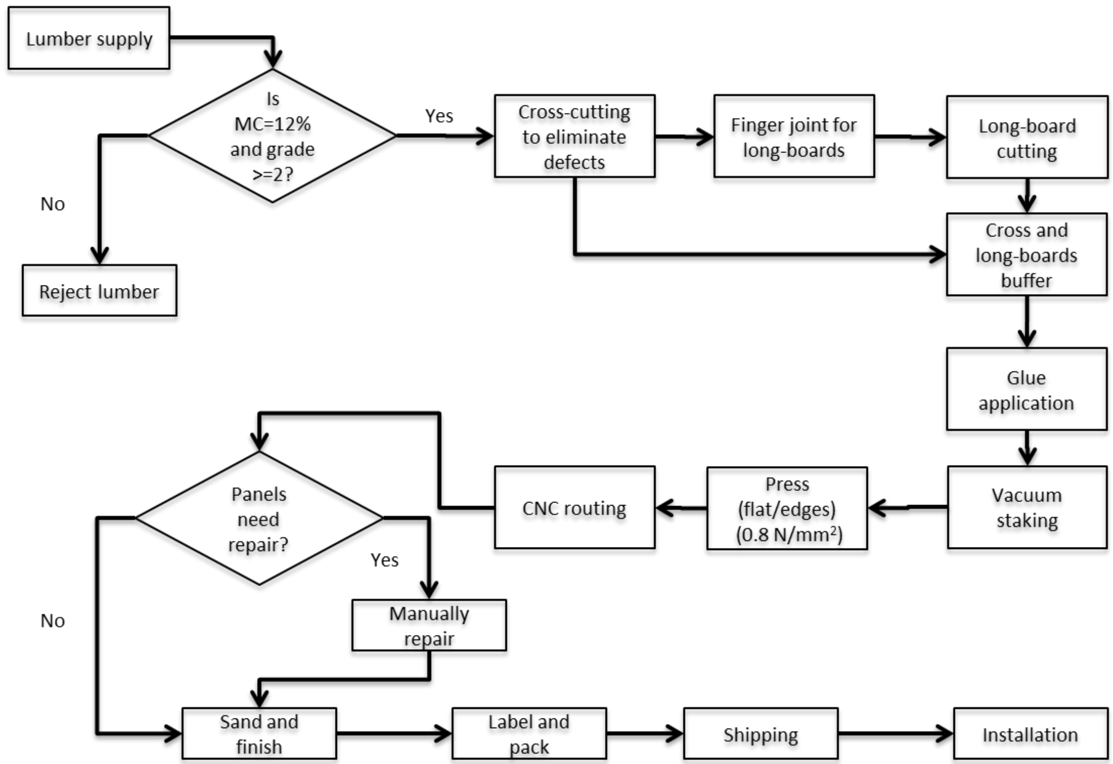

Figure 2-1: Typical CLT production line. Source: Ledinek, 2018.

Based on Europe's existing practices and the PRG 320 manufacturing guideline, CLT manufacturing can be completed in the following seven sub-processes:

1. Lumber preparation
2. Finger-jointing and trimming to the required size
3. Stacking to form CLTs layer
4. Layups and adhesive application
5. Pressing
6. Finishing and matching
7. Delivery

2.3.1.1 Lumber Preparation

Lumber is pulled from the manufacturer's inventory to enter the production line and is de-stacked at a feed-in station. After de-stacking, the lumber's quality assessment occurs, and the moisture content of each lumber piece is measured. Lumber that does not meet the required specifications for CLT manufacturing is sorted out from the production line for additional processing. Lumber with major defects is removed from the process. After sorting, the next step is to grade the lumber visually or by machine. It is then moved to the finger jointing process.

2.3.1.2 Finger-Jointing and Trimming to the Required Size

After processing through the trimming saw to remove the defective parts, the lumber is in random lengths. The lumber is then bonded together lengthwise and trimmed to the required length, according to the designed dimension for parallel and perpendicular layers. Lumber bonding is aided using finger joints. Finger jointing is an efficient method to connect lumber lengthwise (Brandner, 2013). The lumber's clean wood area without wane or knots is selected for the finger jointing to avoid failure. After finger-jointing, the lumber is dressed on all four sides to ensure the required width and thickness and are trimmed to the desired length. Lumber to be used in parallel layers is cut to the maximum length of the press. For the perpendicular layer, lamella is cut to the maximum length of the press width (Yeh et al., 2013) unless a specified dimension is desired.

2.3.1.3 Stacking and CLTs Layer Formation.

Ready to use lumber, commonly known as lamellas, are cut to the required length for the parallel and perpendicular layers, stacked separately, and processed for CLT layer formation. Cross-laminated layer formation can be done in two ways. One method is to manufacture single layers by using adhesives for edge bonding and further processing to form the final CLT panels. The edge bonding method is standard in Europe (Brandner, 2013). Manufacturing single layers with adhesive for edge bonding, limits gaps to an absolute minimum. The second method is eliminating the edge bonding and laminating CLT panels directly from single lamellas (Brandner, 2013). Edge bonding is not required to manufacture CLTs to meet North American Standards under PRG 320.

2.3.1.4 Layups and Adhesive Application

Cross-laminated timber layer formation depends on various factors like the production line design, technology adopted, and mill capacity. Cross-laminated timber panels are assembled using a similar technique to plywood production, where adjacent layers are assembled perpendicularly (Yeh et al., 2013). First, the parallel layer is developed, and the machine spreads the adhesive on top before laying adjacent perpendicular layers. According to Brandner (2013), there are two standards for applying adhesive to the CLT layers. One of the technologies adopted by CLT mills is the fixed layup bed, where a machine moves over a stationary panel to spray adhesive before another layer is placed. The second technology is the fixed machine where the CLT layup bed moves, but the adhesive applying machine remains stationary. When a single panel layup is completed, a metal or plastic separator is added between two panels to avoid adhesion. The number of panels on single layups depends on the CLT layers (3-ply, 5-ply, 7-ply, or 9-ply) on each panel and press capacity.

2.3.1.5 Pressing

After applying adhesive, each panel is immediately pressed to form a solid CLTs structure. The pressing force must meet the specifications of the adhesive and lumber species. Equally distributed adequate pressure is essential over the whole CLTs layer surface to guarantee a consistent and defined bond line (Brandner, 2013). The pressure for face bonding must consider the lumber characteristics and lumber species because too little or excessive pressure reduces the bond line quality and impacts CLTs' strength. Excessive pressure can harm the wood cell structure, leading to lower adhesive penetration. Too little pressure restricts adhesive penetration and causes weak bonding between layers. Weak bonding between layers reduces shear resistance and lowers CLTs' strength (Brandner, 2013).

2.3.1.6 Finishing and Matching

Cross-laminated timber panels from the press come with excessive adhesive on the edge of the panels which is removed by edge trimming, and panels are then cut to the design specifications. Additionally, the panels may be dressed or sanded. Cross-laminated timber is usually produced as a predesigned structure for architectural plans converted to specific production orders (Yeh et al., 2013; Brandner, 2013). Each panel for structural application has a unique position in the building, so each panel requires different work to prepare it as the opening for a door, window, utility duct, architectural design, or detail for connections and joints (Grasser, 2015). All CLT panels are customized according to the end-use by cutting, trimming, milling, and drilling to match the design specifications.

2.3.1.7 Prepare for Delivery

CLT manufacturing's final step is product marking with manufacturing information and proper packaging to ensure its quality. Product marking is a minimum requirement of the PRG 320 standard. Product marking provides the minimum information required to the customer and guarantees that the product meets the required standard. Additionally, marking ensures that the manufacturer is certified by an approved agency (Grasser, 2015, PRG 320). The finished product is packaged to protect it from harsh weather conditions and prepared for shipping. All the assembly parts are collected at the installation site, where the structure will be constructed.

2.3.2 **Current CLTs Market and Lumber**

Production of CLTs for the US's structural market was projected to grow at a compounded annual growth rate (CAGR) of 16.2% starting in 2017, with a $1.833 billion market value by 2024 (Energias, 2018). Murphy (2020) defines CAGR as "*the rate of return that would be required for an investment to grow from its beginning balance to its ending balance, assuming the profits were reinvested at the end of each year of the investment's lifespan*." Energias (2018) also estimated that the North American region would have the highest CAGR from 2017 to 2024. Another research firm, The Beck-Group (2018), a Portland Oregon-based forest product planning and consulting firm, also estimated the US's CLTs' production capacity in 2020 would reach approximately 257,700 m^3. This estimation assumed that all CLT manufacturing facilities would run at full capacity, and 424 bf of nominal lumber would yield one cubic meter of finished CLTs. The Beck-Group (2018) concluded that the estimated CLT production volume for 2020 would require approximately 1.95 billion bf of lumber if all the lumber consumed were 2" x 6" or 2" x 8".

The Beck-Group, (2018) also estimated a structural grade CLTs demand of 515,400 m3 by 2025, and this projected production volume requires approximately 3.9 billion bf of 2" x 6" or 2" x 8"-nominal dimension lumber. If CLT manufacturers only choose to use softwood lumber, approximately 17% of the total lumber produced in the US would go toward CLT manufacturing to meet the demand predicted for 2025 based on the 2017 production volume of softwood lumber.

CLT construction requires 100 to 220 pounds of lumber per cubic meter of space to construct a five-story structure compared to 48 to 60 pounds of lumber per cubic meter of light timber frame construction (Ramage et al., 2017). This number indicates that CLT construction uses double the lumber volume required to construct a light frame structure. However, CLTs are not competing with light-frame structures as a construction material but because of increases wood consumption in mid-and high-rise building construction by replacing concrete or steel. Therefore, the lumber demand for CLT will be in addition to the existing demand for softwood lumber unless the housing industry uses CLTs. Presently, residential housing is not considered cost-effective for CLT construction (Ramage et al., 2017). Thus, there will be a substantial increase in softwood lumber demand coinciding with CLT’s demand.

2.3.3 Available Lumber Volume and Opportunity

The demand for lumber in the US has increased continuously for the last five years. The growth of CLT industries will add additional lumber demand in the coming years. The production volume of lumber increased each year from 2013 to 2018 for both hardwood and softwood species. The demand for softwood lumber is far higher than the US production capacity, shown in Figure 2-2. The gap between consumption and production grew continuously from 2013 to 2018. Hardwood lumber production surpassed the demand for all years for the same period. The difference between hardwood lumber production and consumption has continuously increased in recent years, and manufacturers struggle to market their products. Additional production capacity for softwood lumber is needed to meet the current demand, and additional market opportunities are needed for hardwood lumber.

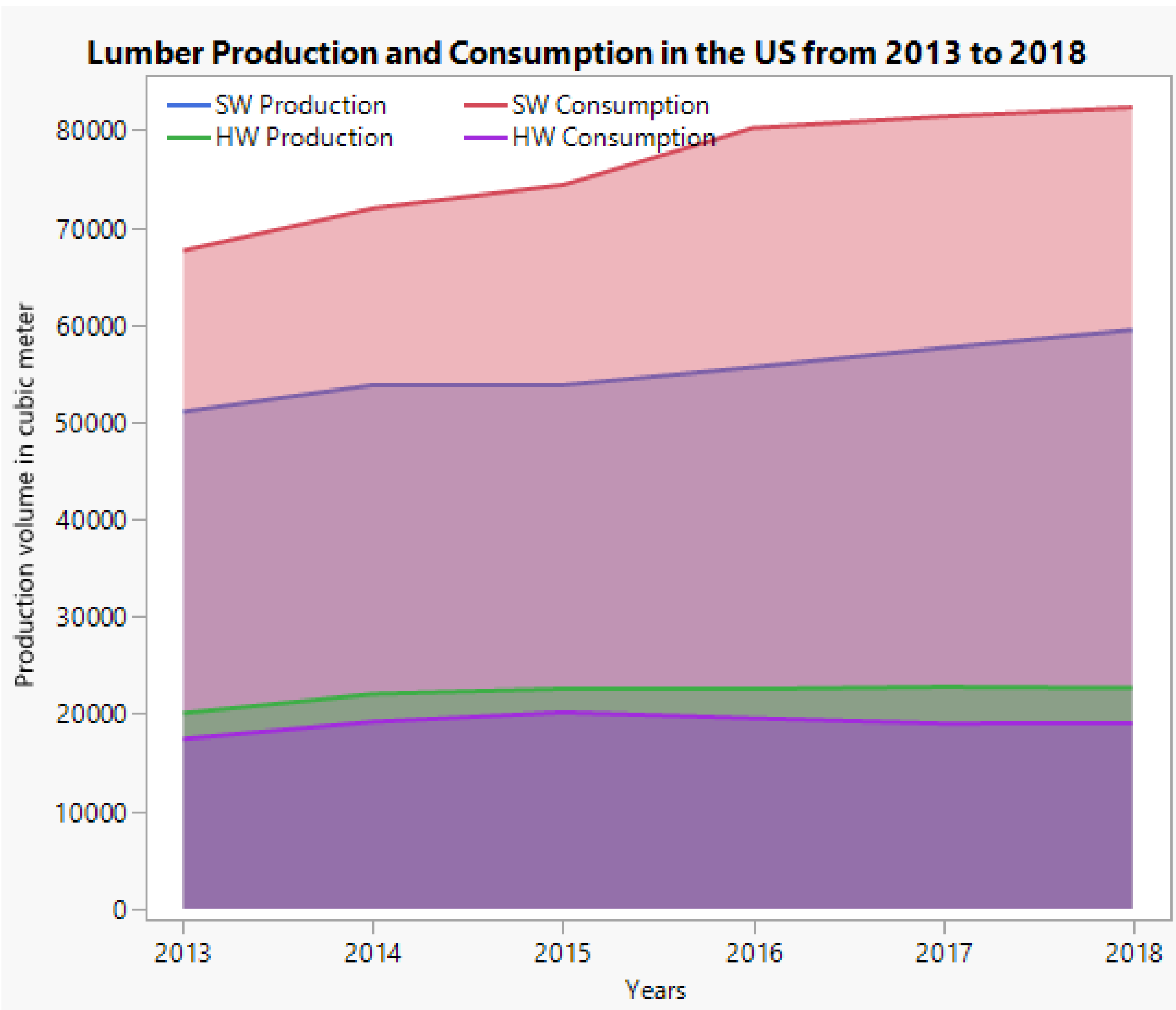

Figure 2-2:: Lumber production and consumption in the US from 2013 to 2018 , Source: FAO (2019) and Howard et al. (2018)

2.4 CLT Production Cost

There was limited information on CLTs' production costs. Manufacturers did not provide the actual cost of CLT production due to company policy; thus, there were very few articles on production costs. The first available published CLTs cost analysis in North America was by FPInnovations in 2011. This study was carried out through simulation using the two different plants located in Canada's eastern and western regions. This study used large-scale plants with the potential to manufacture two different kinds of CLT panels with three or five layers. The cost parameters were resource inputs, capital investment, labor employed, the facility's energy consumption, delivery of the CLT panels, and the adhesives' cost. The percentage values of the different parameters considered in this evaluation are listed in Table 2-4.

Table 2-4:Simulated CLT production cost by the process, Source FPInnovation,2011.

Factor	Wood	Adhesive	Energy	Labor	Packaging	Shipping	Financial expenses	Equipment maintenance	Others
Cost %t	53%	8%	2%	15%	1%	2%	11%	3%	5%

This simulation considered the value of lumber as $400 per 1000 bf. Each plant's initial investment was estimated at $41 million, with 106 million cubic feet production capacity per year. Cross-laminated timber with three layers was supposed to be produced with a panel thickness of 3.46 inches, and five-layer panels were 5.66 inches thick. CLTs production's overall variable cost was estimated at $17 per cubic foot from the simulation analysis, with a two-dollar fixed cost.

The Beck Group (2015) completed a high-level economic feasibility study for the CLT mill and determined the CLT production cost. The primary lumber species identified as 2 x 6 and 2 x 8 Douglas Fir and White Fir, and the estimated lumber value at $355 per 1000 bf. The Beck Group (2015) estimates the production cost of $464.75 per cubic meter of finished CLT panels. The percentage of lumber value on total production cost was determined as 59%. Brandt et al. (2019) completed a techno-economic analysis of two hypothetical CLT manufacturing facilities, a small and large-scale facility (52,000 and 87,000 m3/yr.). The analysis was completed with different capital and operational structures for two facilities keeping the same underlying financial assumption. This study considers that the lumber cost is 35% and 41% for small and large mills. The calculated CLT mills gate value is $536 and $652 per cubic meter for large and small mills. The lumber value was assumed as $359 per 1000 bf without the delivery cost. The following section discusses the possibilities and opportunities for using hardwood in CLT manufacturing based on North America's status.

2.5 Hardwood Lumber and CLTs.

2.5.1 Growing Stock in the National Forest and Timber Inventory in the US

The growing stock of US forest land has continuously increased over the last 80 years. The hardwood volume has shown a much greater growth than softwood, as shown in Figure 2-3. The hardwood forest growth rate is almost double that of the softwood forest growth rate.

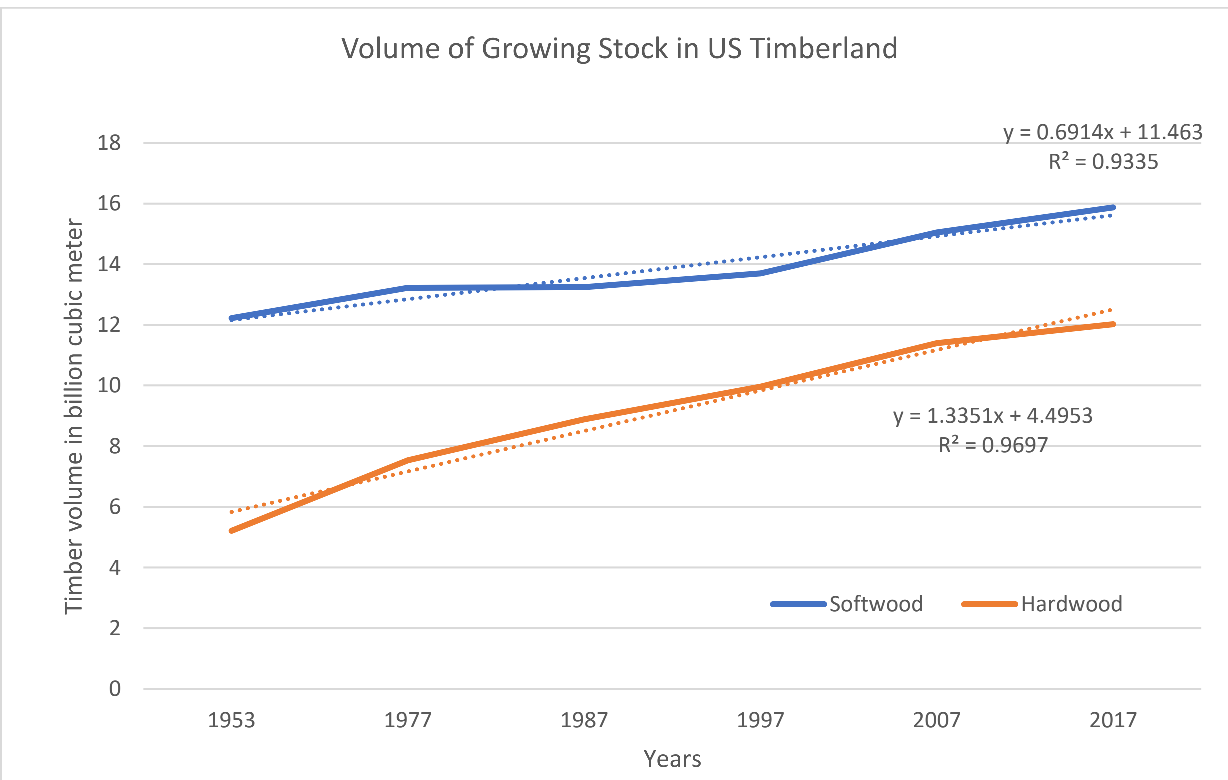

Figure 2-3: Volume of growing stock in US timberland; Source: Oswalt et al. (2018)

The increased growth over time and volume of the growing stock estimated by Oswalt et al. (2018) is presented in Figure 2-4. Softwood has almost double the net growing stock volume than hardwood in US forests. The hardwood growing stock's removal is only 43.3% compared to 57.5% of softwood, leaving more hardwood timber in the forest. Hardwood has a higher mortality percentage than net growth, which is approximately 45%, 7% higher than softwood, as shown in Figure 2-4. This growth in the number of dead trees is the primary fuel that causes the spread of forest fires. Thus, it is necessary to develop a strategy to remove more hardwood lumber from the forest to improve forest health and avoid big forest fires. Hardwood lumber removal can be increased by expanding the hardwood lumber market.

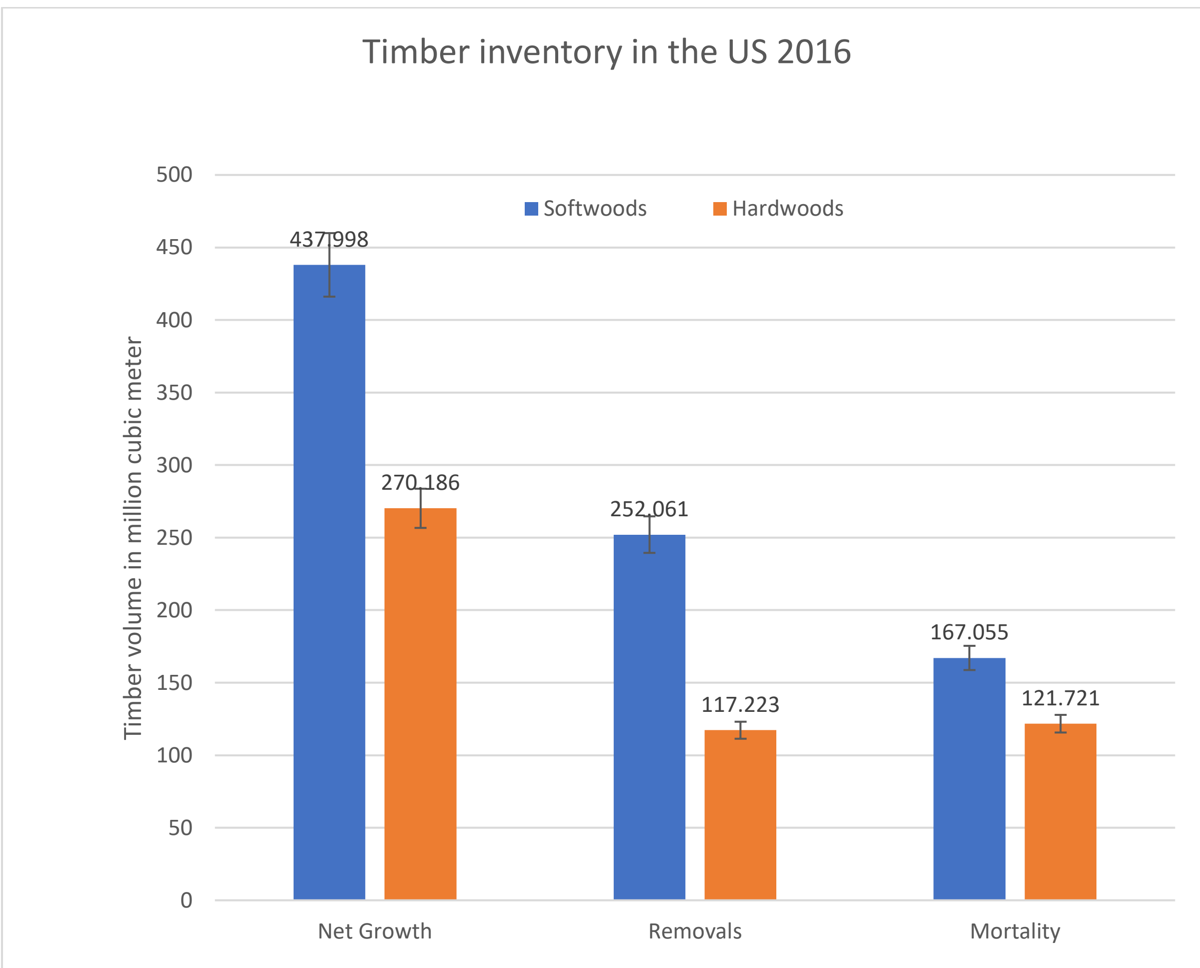

Figure 2-4: Timber inventory in the US in 2016; Source: Oswalt et al. (2018)

2.5.2 Hardwood Market in the US.

The hardwood lumber market in the United States has evolved through many ups and downs in the past decades. The hardwood lumber market reached its peak in 1999 and continued to decline until 2010. In 2011, it began to go up again. After decreasing production from 14 billion bf in 1999 to 6.6 billion bf in 2009, the US hardwood industry has shown signs of recovery (Snow, 2017). By 2016, the US annual hardwood lumber production had reached 9.3 billion bf (Tucker, 2017). However, US hardwood lumber might not reach the production levels that it had 20 years ago. The largest consumer of graded lumber, the furniture industry, has shrunk to below 7% (UNECE 2015). The hardwood lumber industry's market composition has changed from primarily furniture manufacturers to the pallet, industrial, and export markets (Quesada, 2018). The volume of pallet graded lumber, industrial lumber, and the export market has grown from 40% in 2008 to 77% of the total market in 2016 (Buehlmann et al., 2017; Snow, 2017).

In 2007, hardwood accounted for approximately 43% of the 403 billion cubic feet of the total growing stock of trees in the United States, 90% of which was grown in the eastern US (Combo et al., 2009). The US hardwood sawmill industry is a highly fragmented industry that consists of mostly small, family-owned mills. The majority of US hardwood lumber is manufactured by small to medium-sized sawmills located primarily in the United States' northern and southeastern regions (Luppold, 2015).

2.5.3 Hardwood Lumber Production

There are slight variations in hardwood sawmill operations, but the process can be generalized. The sawmill processing discussed here is one of the representative sawmills that operates at an industrial level on the Virginia and North Carolina border. The overall production process is shown in Figure 2-5. Value-added work in hardwood sawmills begins after the logs are unloaded at the primary inventory site. The sawmill can choose tree and log grade species according to the type of mill and technology they have adopted and the market status. First, logs are processed; each is measured for scaling diameter, length, log-grade, sorted according to species and put in the queue for the sawing process.

In the production, line logs are first processed through a debarking machine and forwarded to a metal detector. If the logs pass the metal detection test, they are forwarded to the primary sawing process. If they have failed the metal detection test, they are removed from the queue for metal parts removal. Hardwood sawmills have three different primary saws, a band head rig, a circle head rig, and a Scragg head rig. Logs are broken down in up to 4" flitches from the outer side of the log. Sawing 4" lumber continues until the log has two or four flat faces, depending upon the diameter of the log being processed. When a log is sawn from the outer portion to obtain rectangular wood, they are called cants. These cants and flitches are resawn by secondary saws such as a gang saw or a band resaw. Sometimes cants are removed from primary sawing to sort as the final product.

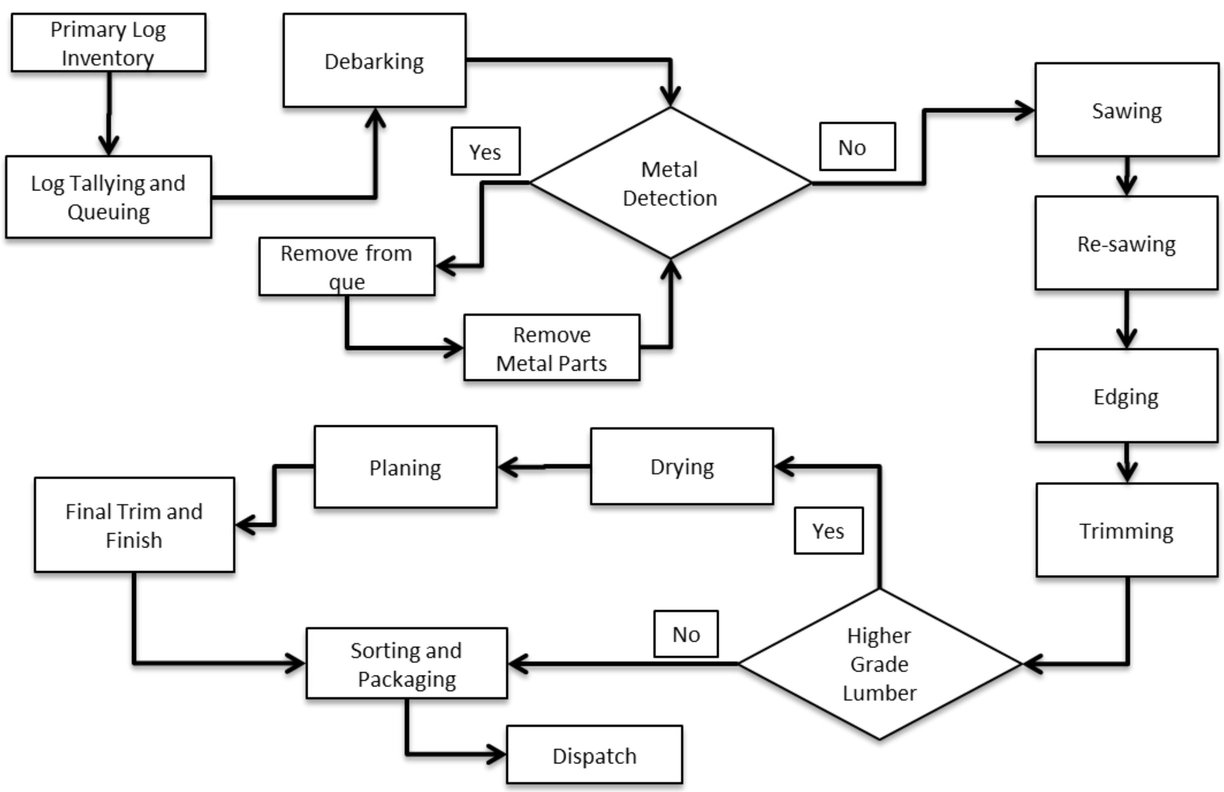

Figure 2-5: Typical hardwood sawmill process, Source: field visit observation

After resawing the flitches and cants, all lumber and cants are trimmed by an edger, if necessary. During trimming, lumber is initially cut parallel to the length, and it is end trimmed by trimmers parallel to the board's width. Most sawmills saw boards to a thickness between ¾" to 4" thick, varying lengths from 4-16 feet, and a width of 4" -20". Lumber is then graded using the NHLA grading rules and sorted for further processing.

After this primary grading, there are two different practices in hardwood sawmills. Depending upon the lumber market and consumer, the sawmill must decide whether to sell green lumber or dry it. When drying lumber, some of the sawmills air dry the lumber, and some of the manufacturers' kiln dry. Sawmills kilns dry the lumber if the lumber is sold for wood products for interior use. Generally, kiln-dried lumber is used in flooring and cabinetry work. The furniture industry and millworks need kiln-dried lumber to avoid shrinkage and other deformations in the final product.

In a kiln-drying process, sawn lumber is inserted into kilns and loosely stacked. Initially, high temperatures and high humidity are maintained in the kiln, and heated air is circulated. The humidity level inside the kiln is gradually reduced while maintaining high heat and circulating forced air. When the humidity level drops, the wood begins to lose moisture. As the process continues, the lumber loses moisture without compromising the strength or causing the wood cells' deformation, making the lumber more valuable.

2.5.4 **Log Grading**

Before processing logs through the sawing process, the logs are graded, sorted, and queued. Two types of grading practices are used for grading hardwood logs in the US, "clear-cutting" and "clear face." The United States Forest Service (USFS) has established a log grading methodology based on the yield of "clear cuttings" from the second-worst face. These grading rules consider three different factors for the log grades: the log portion from the tree, the dimension of the log, and the number and location of defects on the face that will be graded. The total length of the cutting required for each log grade is shown in Table 2-5.

Table 2-5: Total cutting length required for clear-cutting log grading rules; (Source: Kenna, 1981)

Log Length (feet)	*Grade F1 (5/6) yield*	*Grade F2(2/3) yield*	*Grade F3(1/2) yield*
8	-	6’ (3/4 yield)	4’
10	8'4"	6'8"	5'
12	10'	8'	6'
14	11'8"	9'4"	7'
16	13'4"	10'8"	8'

In clear-cutting log grading, the log is aligned into four equal faces that measure one-quarter of the circumference and extend the log's whole length without overlapping. The first face is selected to include as many defects as possible, marked as "worst face," and excluded from grading. All three faces are separately evaluated and ranked as best, second best, and third best face based on the clear area available. For logs considered for lumber grade production, F(factory) grade 1 is the highest, and grade 3 (F3) is the lowest. The log will be assigned a grade according to the percentage of yield. Logs that fall within a grade are predicted to yield a percentage of 1 Common and better grade lumber (Wengert et al., 1994).

Most of the hardwood lumber industry in the US uses a log grading system called "clear face grades." The number of clear (defect-free) faces on the log is the basis for defining the log quality. Clear face grading rules also divide the log into four equal faces. Each face measures one-quarter of the log's circumference, extending to the whole length of the log. This face division is optimized to include defects on a minimum number of faces, leaving another face as a clear face. These clear faces (defect-free faces) are counted to assign log grades. If the log has all clear faces, it is the highest graded log with the clear face of "4." The presence of defects on all the divided faces will reduce the log's grade as low as "0." Many variations on clear face grading rules exist, but, like the USFS system, these rules require minimum diameters and lengths for each log grade (Taylor 2007; Clark et al., 2000). There is no standard clear-face log grading rule in practice.

2.5.5 **Lumber Grading**

Of major importance when considering hardwood lumber for CLT panels is that the lumber must have structural characteristics. Hardwood lumber is traditionally graded based on visual appearance. So, the prevalent grading practice avoids considering mechanical characteristics (Taylor, 2007). The NHLA oversees the grading system for hardwood lumber and depends on clear areas within the log that do not contain defects such as knots, stains, protuberances, and holes within the log (Kretschmann, 2010). Lumber with fewer defects is sorted as higher grades such as FAS, F1F, and Select. In contrast, lumber with larger defect areas and less clear area are assigned grades such as 1 Common, 2A Common, 3A Common, and below grades. Grades and basic rules are presented in Table 2-6

Table 2-6: Hardwood lumber grades, Source: Northeastern Lumber Manufacturers Association, 2013.

Grade	*Trade Name*	*Min. Board width*	*Min. Board length*	*Min. Cutting size*	*Min. Area of Clear cuttings required*
Firsts and Seconds	FAS	6"	8'	4" x 5' or 3" x 7'	83-1/3%
FAS One Face	F1F	6"	8'	4" x 5' or 3" x 7'	83-1/3%
Select	SEL	4"	6'	4" x 5' or 3" x 7	83-1/3%
Number. 1 Common	1C	3"	4'	4" x 2' or 3" x 3'	66-2/3%
number. 2A Common	2AC	3"	4'	3" x 2'	50%
Number 2B Common	2BC	3"	4'	3" x 2'	50%
Number 3A Common	3AC	3"	4'	3" x 2'	33-1/3%
Number 3B Common	3BC	3"	4'	1-1/2"x 2'	25%
Below Grade	BG	Lumber with lower quality than 3BC			
cants	cants	Logs with slabs taken off each of the four sides			

2.5.6 **Machine Grading of Hardwood Lumber.**

In addition to the hardwood lumber's visual grading, one of the technical procedures is the lumber's machine grading. Machine graded lumber is characterized as Machine Stress Rated (MSR) lumber, evaluated with the nondestructive test after it meets the minimum visual appearance (Green, 2005). Each lumber piece is individually evaluated and assigned to Bending and Modulus of Elasticity classes by mechanical stress rating equipment. The MSR graded lumber specification is bending design (Fb) and the corresponding Modulus of Elasticity (MOE) value. MOE is one of the critical criteria for assigning an MSR grade (Green, 2005). Kretschmann et al. (1999) defined mechanically graded lumber as two-inch-thick structural lumber evaluated non-destructively by a machine after visual assessment of specific growth characteristics that the machine cannot or may not evaluate correctly.

Mechanical grading of commercial softwood species has been practiced in the United States since the 1960s (Green, 2005). Green and McDonald (1993) evaluated the relationship between bending strength and tensile strength and bending strength and compression strength parallel to the grain for red oak, red maple, and yellow poplar dimensional lumber. This research concluded that the strength properties of machine graded softwood species could be tested similarly for hardwood species, which eventually forged the concept of mechanically grading hardwood (Green et al. 1993).

Machine Stress Rated lumber grading is not standard in the hardwood industry because hardwood lumber is less commonly used as structural lumber. The value of factory-grade lumber is higher than structural lumber (Green et al., 2007). Manufacturers must control the lumber's moisture content for better yield to produce the machine graded hardwood lumber. Moisture control in strength grading is more critical than visually graded structural lumber (Green, 2005). The higher the moisture content of the wood, the lower the strength properties.

2.5.7 **Hardwood-Softwood Lumber Value Comparison.**

The value of the hardwood lumber is greater than softwood lumber for higher grades. The low-value hardwood lumber value is competitive with softwood lumber, as shown in Figure 2-6. If lower-grade hardwood could be manufactured for structural application, it would be significant for finding an additional market for hardwood lumber. In general, visually graded hardwood lumber from grade 2 common and below is considered low-value lumber. Thus, the production of structural grade hardwood lumber from lower grade logs would be a suitable opportunity for expanding the hardwood lumber market.

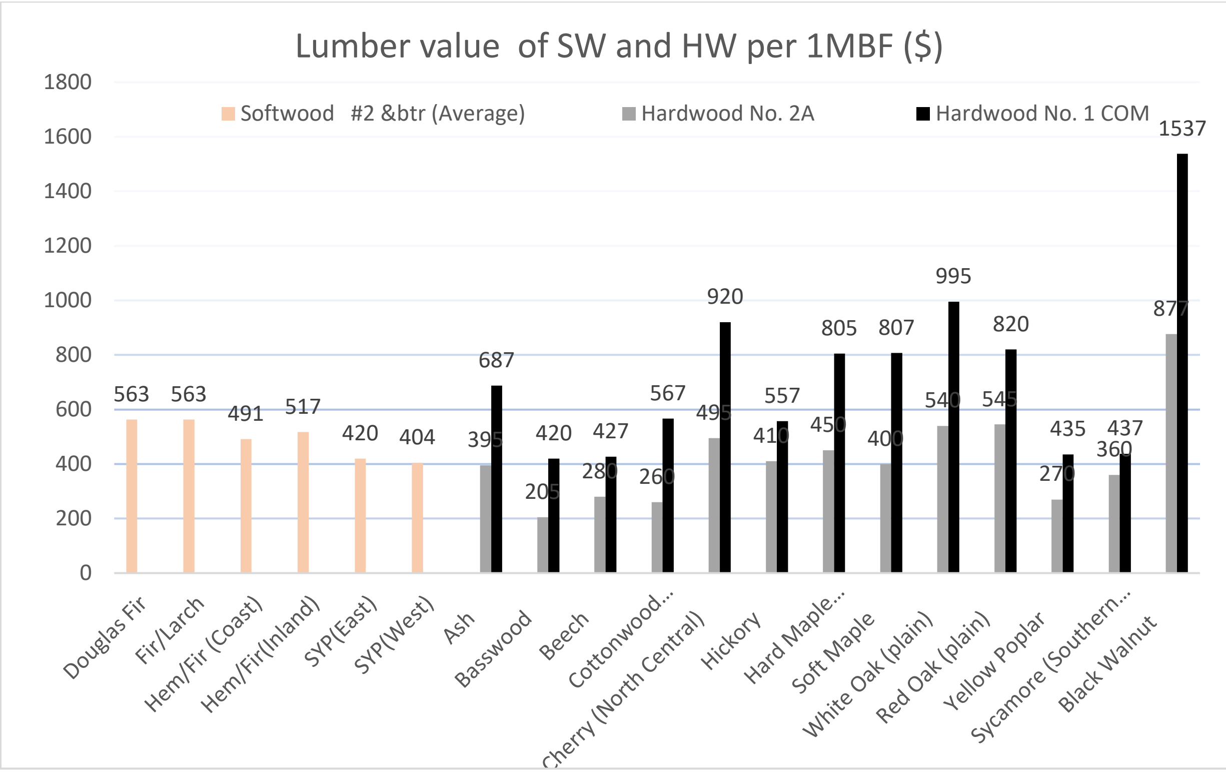

Figure 2-6: Buying cost comparison of softwood and hardwood lumber; Only comparing No. 2 and better softwood lumber and 1 Common below hardwood lumber. Sources: Softwood lumber value s (Madison's Lumber Reporter, 2017), NHLA grade Hardwood lumber value s 1-inch-thick (4/4) kiln –dried, Appalachian market area. (Indiana State Department of Agriculture, January 2018).

2.6 Hardwood Lumber Used in CLT Manufacturing

The standard raw material for CLT manufacturing is softwood structural lumber. As the CLT system experiences industrial production growth, an adequate supply of raw material becomes a primary concern (Muszyński et al., 2017). Initially, CLTs were developed to be manufactured from a single wood species to avoid design failure from different mechanical and strength properties of the wood. Later, CLTs were studied using lumber from different species with approximately similar mechanical and strength properties. With the rise in the use of different lumber species, CLTs from hardwood lumber became one alternative (Grasser, 2015).

It took almost 20 years for hardwood species to be considered for CLT production. Hardwood CLTs are only produced for testing and study purposes but are not produced on a commercial scale. AHEC has continuously worked together with various stakeholders to promote hardwood in CLTs, especially from yellow poplar. Yellow poplar was first used in the construction of Sclera, an elliptical pavilion designed using laminated yellow-poplar lumber for the London Design Festival 2008 (AHEC, 2019). Endless Stairs, constructed in 2013 using 187 CLTs steps, is the first successful yellow poplar CLTs (Slavid, 2013; AHEC, 2019). However, industrial-size hardwood CLT panels were first used to construct "The Smile" for the London Design Festival 2016. The Smile's structure was constructed using 4.5m by 12 m CLT panels manufactured by Züblin -a German company (AHEC, 2019).

In 2017, a major step forward in hardwood CLT use in structural application was completed. Maggie's Centre, a specialist cancer center in the north of England, was completed as the first hardwood CLT building globally (Allen, 2017; AHEC, 2019) and registered as the first application of hardwood CLTs in engineering construction (AHEC, 2019). Twenty cross-laminated timber panels were fabricated using yellow poplar lumber provided by AHEC from the US. Only three-ply and five plies square panel of 106-inch nominal dimensions were produced in Germany by Züblin (AHEC, 2019). In the process, 20 x 95mm and 20 x 145mm finished lamellae were used to fabricate all CLT panels by applying Henkel Loctite Purbond PUR HB S609 adhesive. These panels were manufactured using more than 40% adhesive and pressed for around 5 hours, double the time to press softwood CLTs (AHEC, 2019).

This first success of hardwood CLTs greatly influenced the US hardwood market. The US is the leading producer of hardwood and saw the opportunity to use domestic hardwood lumber as a new construction material. In response to this successful project in the UK, the USFS awarded a $250,000 grant to fund the first hardwood CLT project in the US in 2016. This grant was awarded to IKD, a Boston based architectural firm, to design a CLT project known as "Conversation Plinth" at Exhibit Columbus. This project was designed to use low-graded hardwood, such as 3 common oak, maple, and ash from the region. This hardwood CLTs project was designed to show the effectiveness of low-grade hardwood lumber in CLTs projects in the US and establish a fundamental principle of using low grade hardwoods for CLTs.

The first application of hardwood CLTs in the US for a permanent structure was to build a train observatory in Radford, Virginia. The project was completed as a multi-departmental collaboration by Virginia Tech, led by the College of Architecture and Urban Studies. The structure was designed based on the observed performance results of yellow poplar CLTs by Mohadmadhaz et al. (2015) at the Virginia Tech laboratory. CLTs used in the structure were manufactured using 2 common NHLA grade yellow poplar lumber. Most of the lumber used was of 8/4” x 6’’ dimension. Fifteen CLT panels ten feet long by five feet wide were pressed as plain CLTs and cut into the desired architectural shape using a CNC machine at the Southern Virginia Higher Education Center in South Boston, Virginia.

Five panels were manufactured as three-ply panels, and another ten panels were manufactured as five-ply panels. EP950-A, a structurally rated laminating glue, was used to fabricate these CLT panels. Glue and CLTs layups were completed manually before applying 100 psi pressure for about 90 minutes. The press time was determined based on glue application time. For every minute taken to apply glue that was counted and CLTs were pressed for more than the six times of the glue application time. The press used was small compared to the panel size fabricated; thus, the pressure was not distributed across the edge, causing delamination problems. The required tests on the panel for structural performance were completed in a Virginia Tech laboratory and were satisfactory regarding the PRG 320 standard. Since the production process was manual, it did not provide information for the industrial production of CLTs. The following section will discuss the potential of yellow poplar structural lumber for use in CLT manufacturing.

2.7 Yellow Poplar Studied to Produce Structural Lumber

Over the last 30 years, many studies have researched the use of hardwood logs to produce structural lumber. Yellow poplar and a few other hardwoods are approved for stress grading as structural lumber according to the National Grading Rules for Softwood Dimensional Lumber (Green & McDonald, 1993). It is not commonly used because, as pointed out by Koch et al. (1986), YP is prone to excessive warping on conversion to dimensional lumber by conventional sawing and drying methods.

Dimensional lumber from yellow poplar has been studied using three different practices. One method is to produce structural lumber from whole logs, which was studied by Denig et al. (1984). The second method was the mixed grade lumber production method. For this method, Allison et al. (1987) studied structural grade lumber production sawing NHLA grade lumber from the logs' outer quality zone. Structural grade lumber was sawn from the core of the logs, which is considered as a significant portion of low-grade lumber zone. The third method was to develop a comparable grading system for hardwood and softwood. A comparable grading system would allow hardwood graded lumber with NHLA rules to be re-graded with a hardwood-softwood comparison table for structural use. This method was postulated by Koch et al. (1986). The following section discusses each of these log yield studies to produce structural lumber and the strength and limitations.

Denig et al. (1984) studied developing practical log-grading specifications to identify YP logs economically suitable for producing construction dimensioned lumber. This study showed that 39% of the Number 3 2" x 4" s was upgraded to Number 2 and Better. Twenty-five percent of the Economy grade 2" x 4" were upgraded to Number. 2 and Better. Ten percent of the Economy grade 2" x 4” were upgraded to Number 3 by further processing when Saw-Dry-Rip (SDR) technology was used. The SDR technique has been documented as the appropriate technology to produce SGHL (Maeglin et al., 1983; Alison et al., 1987). Using SDR techniques, green logs are live sawn into nominal two-inch-thick flitches first. Using SDR techniques helps control the lumber's stress due to the pieces' larger size and the symmetry of stresses

(Denig, 1984). Sawn lumber is then dried using high temperatures to reduce the stress further. After drying, the flitches are straight-line ripped to the desired dimension. Thus, producing framing lumber with limited wrapping, crooking, and bending.

This research produced a regression equation to predict the log yield from 8' long logs of various grades and diameters. The minimum and maximum diameter of the logs used for the study was not specified. However, the author mentioned the diameter at the base height (DBH) of the trees ranged from 8" to 23.3". This study only helped explain SGHL the sawing methods' appropriateness, but not the actual yield based on the logs' grade and dimension, except for logs with 8' length.

Because of NHLA grade hardwood lumber's higher value, the lumber yield's economics were a primary concern. SGHL production has been studied using the logs' pith by continuing the NHLA grade hardwood lumber production from the logs' outside zone to maximize the yield. Allison et al. (1987) first studied the development of framing lumber production methods on both hardwood and pine producers. Allison et al. 's (1987) study focused on finding a suitable method of producing YP framing lumber with mills' existing equipment. Their method produced a combination of products to convert the 2B and lower grade NHLA lumber into framing lumber. This study concluded four-square lumber could be sawn from the cants in existing mills using a balanced stress sawing system. The framing lumber could be sawn from the log center, where the majority of the lower NHLA grade lumber is usually found. Allison et al.'s (1987) study proposed setting the gang saw to cut three, 7/4"-green pieces from the center of each cant and NHLA grade lumber from the log's outer portion. The first breakdown was done by head saws, scragg mills, and chipping canters. Two-sided cants were developed, and double arbor gang saws did the secondary breakdown. The observed yield was 87% Number 2 and better. The study result was an acceptable framing grade yield for most southern pine mills. The results showed that a significant percentage of lower grade lumber could be converted to a product with a potentially higher value using this method.

This study was limited in many ways. First, Allison et al. 's (1987) study did not mention the length of the logs used for this experiment and excluded the logs with a diameter greater than 12". Additionally, the lumber outputs were independent of the log grades and presented for the log diameter only. It was also not clear how many logs were there for each diameter group. So, it is not clear which grade of logs produced the higher volume of framing lumber or the process's economics. This study was presented to describe that the lumber's production volume is proportional to the lumber's diameter. Thus, this study can be used to observe the possibility of producing 2" x6" and 2" x8" structural lumber from hardwood lumber for CLT use. Additionally, this study concluded that revenue from hardwood lumber's mixed production would be sufficient to justify the additional investment required to handle and process framing lumber. Lumber value has changed following the market dynamics of the 2008 recession, so it is necessary to pay attention to the present market.

To test the mechanical properties of yellow poplar sawn from the center of logs, Faust et al. (1990) studied the strength and stiffness of yellow poplar and sweetgum lumber. The logs were sawn to produce pith centered 12' long nominal 8" square cants, and cants were broken down on a resaw following a procedure like pine cants. The 2" x 8" were cut first, followed by the 2" x4 " and graded by the defect and warp grades according to NELMA, 1977 rules by a certified lumber grader. Faust et al. (1990) studied twelve-factor treatment combinations formed from two species and two widths. Three defect classes were adjusted with specific gravity as a covariant. After drying the lumber below 12% moisture, the lumber was edged to nominal 1.5’’ x 3.5’’ for the nominal 2" x 4" and 1.5’’ x 7.25’’ for the nominal 2" x 8". The lumber was then tested to obtain an average plank bending modulus of elasticity value and tensile strength test. The observed results from the test are presented in Table 2-7.

These results from Faust et al. (1990) for all mechanical tests comfortably exceed the minimum design value of visually graded yellow poplar mentioned in the NDS-2012 edition supplement. In addition to this, Koch (1983) also studied the relationship of bending strength to the stiffness of YP 2" x 4" s graded by the

National Grading Rule (American Lumber Standard PS-20-70) for softwood dimension. This study showed that strength was strongly related to knot size, but stiffness was less related to knot size and more to wood quality. This study was critical because the relationship between MOR and modulus of elasticity (MOE) of structural lumber is the basis for machine grading. Thus, the conclusion is that the MSR method applies to yellow poplar.

Table 2-7: Strength and stiffness test results of yellow poplar 2" x4" and 2" x8" structural lumber sawn from the center of the logs (Faust et al. 1990).

			Bending MOR		*Bending MOE*	
	Samples Number(N)	Average MC% at testing	Mean (psi)	SD	Mean (10^6 psi)	SD
2x4	142	7.55	6963	2467	1.66	0.24
2x8	105	8.49	4764	2258	1.53	0.59
Combined	247	7.94	6028	2613	1.6	0.43
			Tensile strength		Tensile MOE	
			Mean (psi)	SD	Mean (10^6 psi)	SD
2x4	139	6.9	4818	2467	1.64	0.27
2x8	101	6.55	3214	1810	1.54	0.36
Combined	240	6.75	4143	2348	1.6	0.31
			Compressive strength		Compressive MOE	
			Mean (psi)	SD	Mean (10^6 psi)	SD
2x4	136		5577	944	1.74	0.46
2x8	105		6146	739	1.94	0.6
Combined	241		5825	904	1.83	0.53

Additionally, Gerhards (1983) studied the effect of high temperature drying on YP 2" x 4" lumber's bending strength. The results showed that YP processed with high-temperature drying had negligibly lower bending strength than those processed with conventional sawing and conventional drying. With higher visual quality levels of yellow poplar, the differences in bending strength between high-temperature drying processes and the conventional process were not statistically significant. Gerhards (1983) concluded that MOE is highly correlated to bending strength, which supports the potential of machine grading for yellow poplar.

Koch et al. (1986) studied actual yields of second growth YP logs sawn into 4/4" and 5/4" hardwood factory lumber with the same material graded as select, factory, and standard lumber by softwood rules. Koch et al. (1986) designed the study to determine and compare hardwood and softwood grading based on yellow poplar lumber.

Conventional grade sawing procedures were used to saw one-half of the logs in each combination of log grade and scaling diameter into 5/4" lumber, 1-3/8" thick green. The remaining half was sawn into 4/4" lumber, 1-1/8" thick green. Lumber was kiln-dried to approximately 10% moisture content. Boards were first graded for hardwood factory lumber by NHLA rules. Softwood rules were used to grade the boards as softwood selects, D Select and better, molding and shop, and common by an official inspector of the Northern Hardwood and Pine Association. Based on the results of this study, the second growth YP exhibits considerable potential to produce millwork. For purchasers of softwood who consider buying YP graded by NHLA rules, this study determined that the lumber grades shown in Table 2-8 are approximately equivalent:

Table 2-8: Softwood grades compared to hardwood grades, (Source: Koch et al. 1986).

Thickness	*4/4"*		*5/4"*	
Grade	Fac Sel	Number 1 Common	Fac Sel	Number 1 Common
	Number 1 Shop	Number 2A Common	Number 1 Shop	Number 2 Common
	Number 2 Shop	Number 2A Common	Number 2 Shop	Number 1 Common
			Number 3 Shop	Number 2B Common

Koch et al. (1986) also compared the economics of buying 4/4" and 5/4" yellow-poplar FAS and Number 1 Common hardwood factory to replace FacSel structural lumber. The value used by Koch et al. (1986) was $440/1MBF and $270/1MBF for 4/4" and $450/1MBF and $275/1MBF for 5/4" FAS and Number 1 Common, respectively, where the value of the FacSel was $485 for 4/4" and $630 for 5/4". The results indicated that the hardwood sawmill could potentially yield more revenue by manufacturing structural lumber, which would need to be reevaluated at the current market value. This study was limited to explaining the volume comparison of lumber outputs from the sample logs to make a fair comparison for the yield and revenue.

The critical factor for a sustainable market is the economic viability of the changes in the existing process. Structural lumber production from hardwood also needs to be economical for adoption by sawmills. Ringe (1988) studied the feasibility and competitive nature of YP structural lumber using value-added analysis. The value-added in converting various sizes and grades of YP logs into factory lumber was compared to the value-added in converting them into structural lumber. Ringe (1988) used the Denig (1994) regression equation to predict the lumber yields for structural lumber yields from the logs' different grades based on diameter. For factory-grade lumber, the yield results from Hanks et al. (1980) are considered log-yield. Ringe (1988) stated that yellow-poplar is very similar to the spruce-pine-fir (S-P-F) group. The stress ratings of YP and SPF group lumber are nearly identical. Therefore, the value of the SPF group proxies for YP for economic analysis is, due to the lack of published values for structural lumber from YP.

Ringe’s (1988) results showed that the value-added in sawing factory lumber was, in almost all cases, substantially higher than that measured in sawing structural lumber. On average, value-added increased as log grade declined. Although this increase was only 7% between the US Forest Services F1 and F2 grades, it was a much-noticed 24% between the F2 and F3 grades. This result indicates that as grade declines, log costs decrease faster than the lumber's value, which helps when considering using structural lumber from low-grade logs. This study also concluded that YP structural lumber could be competitive with some Douglas-fir grades and southern pine produced by conventional sawing technology. This same study also suggested that conversion to structural lumber is a possible alternative for YP in some cases. Ringe (1988) concluded that the production of SGHL from yellow poplar was only possible if the lumber producer were to find an expanded market because it produced lumber on an optimized scale in the existing setup. The new market opportunity could be CLTs' raw material. Yellow poplar can meet the mechanical and physical requirements for CLT use. Yellow poplar is also sufficiently available in the southeastern US. Cross-laminated timber producers in this region can consider producing both visual graded and strength graded CLTs from YP.

In summary, it seems practical to produce YP dimensional lumber, though drying in high kiln temperatures to minimize warp is essential. Denig et al. (1984) developed SDR technology to reduce warp and crook. Allison et al. (1987) developed a technique to produce mixed lumber grades to produce SGHL from logs' pith to optimize the yield. Koch et al. 's (1983) study to compare yellow poplar lumber graded with both NHLA and softwood grading rules and economic comparison supported the feasibility of producing structural lumber from yellow poplar. Faust et al. 's (1990) mechanical properties tests of yellow poplar's structural lumber values from the center of logs compared to NDS values support manufacturing structural lumber's feasibility. The study by Koch (1983) and Gerhards (1983) supports the practice of using MSR grading for yellow-poplar lumber, which can be an appealing factor in switching to structural lumber production from hardwood. Recently, there has not been much study on yellow poplar logs for structural use. The price dynamics of the logs and lumber have changed with the changing market. The yield to produce 6" and 8" SGHL as a product mix with NHLA grade lumber from the core of yellow poplar is hard to evaluate at the current lumber value with references available in the literature and log yield studies because none of these studies had considered producing only 2" x 6" and 2" x 8" lumber and compared the revenue. The yield and revenue will be different for producing 2" x 6" and 2" x 8" lumber. Table 2-9 summarizes the results and limitations of some of the significant log-yield studies discussed in the literature.

Table 2-9: Existing literature on yellow poplar, results of the study, and limitations.

Study	Results	Limitations
Denig et al. (1984)	It postulates the regression equation to predict the yield of structural lumber for all logs according to the defect grade defined by USFS.	The regression equation developed is independent of the length. Lumber grade is likely to improve as length increases from 8 foot to 10- and 12-foot logs.
		The equation is developed to manufacture all structural lumber, so it may not apply to mixed lumber production.
Allison et al. (1987)	A significant percentage of lower grade lumber could be converted to a potentially higher value with a mixed lumber production process.	The length of the logs used for this experiment is not given. It excluded logs with a diameter greater than 12 inches.
		The lumber outputs are independent of the log grades and are presented based upon log diameter only.
		The number of logs for each diameter group is also unknown. So, it is not clear which diameter-grade of logs has produced a higher volume of framing lumber or the process's economics.
		This study was conducted in the mid-1980s, so the process's economic analysis must be updated for the present market. The log and lumber value s have changed based on changing market dynamics from the 1990s.
Koch et al. (1986)	This research concluded that second-growth yellow poplar exhibits considerable potential to produce millwork.	Developed a grade equivalence between hardwood and softwood for 5/4" and 4/4" thick hardwood lumber sawing only and excluded other thickness groups.
	He established a relationship for comparing hardwood lumber grades and softwood lumber grades.	This study's first idea was to reduce low-grade lumber from hardwood by sawing structural lumber from the logs' center. However, this study compared the hardwood and softwood grade equivalence and found the hardwood grade conversion percentage into softwood equivalence.
		The results support YP's possibility as structural lumber and demand the economic analysis at a current value since the log and lumber value dynamics in the US lumber market have changed from the 2008 recession.

Study	Results	Limitations
Ringe (1988)	The existing factory lumber industry was putting resources to their most profitable use for yellow poplar. The production of structural lumber from YP required additional market opportunities with a higher return.	Both log yield values were derived from the prediction equation and model, so it did not represent the actual log yield. Denig's (1984) study was conducted independently of log lengths. It only mentions the logs' grade, but there are minimum length requirements for them to be in a higher-grade group. However, no maximum length was specified.
		The economic comparison was conducted based on a proxy value, which may not represent the lumber production cost.
		The structural lumber considered for the study only represented the estimates for 2" x4" lumber. However, this study focused on sawing 2" x6" and 2" x8" lumber from the logs' pith while producing NHLA grade lumber from the outer zone.
Gerhards (1983)	High temperature drying of YP lumber had negligibly lower bending strength compared to conventional drying.	The study produced only 2" X 4" lumber from YP, and 2" x6" and 2" x8" were excluded. These widths are the primary focus of this study.
	MOE is highly correlated to bending strength, which concludes that machine grading is applicable.	This study also does not compare the economics and yield for structural lumber production.

2.7.1 **Yellow Poplar to Produce SGHL.**

Yellow poplar, also known as soft hardwood (Cassens et al., 2009), is an abundant timber source in the United States' eastern region. Yellow poplar accounts for nine percent of the sawn timber in eastern hardwood forests (Smith et al. 2001). Additionally, YP is a relatively low value timber source. The values of stumpage in the eastern region ranged from $84- $532 based upon log grade (Ray, 2018). The average log value is $240 per MBF according to lumber volume predicted by International ¼, comparable to the average value of the dominant softwood species published by Northeast Timber Exchange, LLC (2018) August 2018.

Cassens et al. (2009) describe YP timber as a fast-growing, easy to schedule, fast to dry, and easy to machine timber species, which has higher mechanical and physical properties than similar density woods and properties comparable to softwood (SPF-group) lumber. Because of the similar properties to some of the softwood species, YP has been studied for construction grade and is listed in the NDS for Wood Construction published by the American Forest and Paper Association (Cassens et al. 2009). The relative mechanical and physical properties of yellow poplar presented by Cassens et al. (2009) are summarized in Table 2-10.

Table 2-10: Physical and mechanical properties of the yellow-poplar; Source: Cassens et al., 2009.

Categories	Properties
Workability	The average rating for its planing, shaping, turning, and boring qualities.
	It is a medium-density wood prone to fuzz or tear, which can be reduced using sharp tools.
Strength	At 12%, MC, MOE, and MOR are relatively high compared to other woods of similar densities.
	Mechanical properties of yellow poplar are comparable to the softwood lumber category called spruce-pine-fir (SPF)
	Construction grades of yellow poplar are listed in the NDS for Wood Construction published by the American Forest and Paper Association.
Drying	Easy to dry with a moderate kiln schedule but requires being stacked and appropriately weighted to avoid warping
Shrinkage	Intermediate in shrinkage

2.7.2 **Yellow Poplar for CLT Manufacturing**

In North America, the structural use of lumber is conventionally dominated by softwood species. Hardwood species were studied for structural grading when grading techniques for structural timber were implemented initially (Denig et al. 1984). However, due to lack of economic advantages, hardwoods have never been successfully manufactured as structural dimension lumber (Grasser, 2015). They were left behind with the traditional sawing practice of random length and width. Due to low economic margins, sufficient availability of softwood lumber, and mechanical properties to meet the design requirements, hardwood lumber is not manufactured as structural lumber and is mostly produced in random width and length (AHEC, 2008). There has been some effort to use hardwood lumber in structural construction. The one species of hardwood that occasionally appears on the structural market is YP (Green, 2005). Yellow poplar exhibits some excellent structural use properties and is considered easy to machine and plain (Koch et al. 1986). Some of the mechanical properties of YP lumber are presented in Table 2-10 and Table 2-11. In addition to this, YP has shown secure connection and finishing properties (Grasser, 2015), making it more attractive for structural use. The remarkable physical and mechanical characteristics of YP lumber have been studied for structural use for many years. The new studies on YP are more focused on promoting it as CLT raw material in the US. The following section discusses the North American CLT standard and yellow poplar in detail.

2.7.3 **North American CLTs Standard and YP**

Cross-laminated timber manufacturing with YP lumber is feasible, as research and pilot projects have already proven (Beagley et al., 2014; Slavid, 2013). It has the lumber properties needed to be considered for a CLT raw material according to the existing PRG 320 standards. YP properties and PRG 320 standards are compared in Table 2-11.

Table 2-11: CLTs requirements and yellow-poplar lumber; Source: Grasser, 2015

Requirements Standard	YP	Source
Recognized by the ALSC under PS 20	Number	(ALSC, 2010, PRG 320)
Specific Gravity above 0.35	Yes (0.43)	(NDS, 2012 PRG 320)
Minimum lamination grade primary strength direction: 1200f-1.2E MSR; Visual Number 2	Yes (Visual Number 2)	(AWC, 2014, PRG 320)
Minimum lamination grade minor strength direction: Visual Number 3	Yes	(AWC, 2014, PRG 320)
CLTs Grade for YP	None	(PRG 320)

Considering the properties of the adhesives currently used in CLTs production, CLTs from YP is feasible for fabrication with 1K PUR (Slavid, 2013). Although YP lumber meets most CLT raw materials' physical and mechanical requirements, there has been some limitation in promoting the products at the industrial level. Understanding the actual status will require more study and research. Some of the studies examining the possibility of using YP in CLTs are discussed below.

Research conducted at Virginia Tech to use YP as feedstock for CLT produced significantly positive mechanical test results. Six 5-layer CLTs beams (101" x 6" x 3.13") were fabricated and tested non-destructively. The research focused on four mechanical based stiffness computing methods and their applicability for predicting hardwoods' strength (Mohamadzadeh et al., 2015). The nondestructive test of YP CLTs met the strength requirements on effective bending stiffness (EIeff) and effective shear stiffness (GAeff) for the current North American CLTs standard (Mohamadzadeh et al., 2015; Beagley et al., 2014). Research conducted at the University of Trento in Italy examined the strength properties of CLTs. This study concluded that YP CLTs have three times more strength and stiffness under rolling shear than other softwood (Slavid, 2013). The same research also concluded that YP lumber is an ideal raw material source for CLT manufacturing. Some researchers have pointed out that there are some limitations to using YP in the CLT manufacturing process. The limitations are listed below:

- YP produced in industries is of a random length and random width (AHEC, 2008). It is necessary to establish new sawing techniques to promote uniform dimensions of lumber. Random processing dimensions of lumber added more production costs, reducing the economic feasibility.
- Another concern of using YP as a feedstock for CLT was the raw material value (Grasser, 2015). The average value of random length YP in March 2018 was about $450 (AHC, 2018). Simultaneously, the softwood lumber (SYP) average value was about $360 (Madison Report, 2018) in North America.
- All lumber to be used in CLTs fabrication must be kiln-dried to 12±3% moisture content. The prevalent practice of hardwood lumber production avoids kiln-drying lower-grade lumber (Taylor, 2007; Grasser, 2015).
- Additionally, value-added work of low value hardwood lumber requires economic analysis to evaluate the competitiveness with currently used softwood species.

- CLTs from low value hardwood lumber exhibits better mechanical properties (Beagley et al., 2014). However, it is necessary to evaluate overall performance to consider these CLTs for construction use.
- Although YP would fulfill the requirements for specific gravity and lamination grades, the species' utilization, according to the standard, is not feasible at this point (Grasser, 2015). The ANSI/APA-2017 standard does not consider any hardwoods.

Considering these limitations and opportunities of YP lumber, the existing problems, and opportunities for hardwood lumber as CLT raw material pointed out by the various researchers are summarized in Table 2-12 (Beagley et al., 2014; Espinoza et al., 2016; Quesada, 2018).

Table 2-12: Problems and opportunities with hardwood lumber in CLTs

Problems	*Opportunities*
Only softwood lumber is recognized under ALSC under PS 20 in the US and CLSAB under CSA O141 in Canada. Only lumber, which has a specific gravity of 0.35 as published in NDS, can be used.	Most hardwoods have design values in NDS, and most hardwoods have SG higher than 0.35
Hardwoods are commonly sawn to 4/4" thickness and random width.	Hardwood can be sawn to produce a product mix of NHLA and NELMA lumber.
All lumber to be used in CLTs fabrication must be kiln-dried to 12±3% moisture content, but not all hardwood lumber is kiln-dried.	Hardwoods can be dried to low moisture contents of approximately 8%
A higher capacity press is needed for hardwood CLTs due to the higher stiffness.	Some of the hardwoods exhibit higher mechanical properties than softwoods.
Higher density could cause more stresses in the bond line due to more considerable structural changes from MC variations.	Some of the hardwood graded as 2 common and lower could make up Number 2 and better.
Extractives in hardwood could interfere with gluing, possibly due to acidity change.	Most of the lower grade hardwood lumber value is competitive with softwood.

CHAPTER 3. HARDWOOD LUMBER IN CROSS LAMINATED TIMBER

3 Introduction

Cross laminated timbers were first introduced in Europe (Kremer et al., 2015; Mohamadzadeh et al., 2015). In the beginning, CLT panels were designed to be manufactured from a single wood species (PRG 320, Grasser, 2015). Single species were chosen to avoid possible design failures due to differences in the wood's mechanical and strength properties (PRG 320; Grasser, 2015). North American manufacturers can use multiple species in a single CLT panel (PRG 320). The use of numerous lumber species in a single panel is allowed if the lumber has similar mechanical and strength properties. However, this definition excludes lumber from hardwood species. The revised version of PRG 320 in 2015, 2017, and 2020 does not recognize hardwood lumber as a raw material. With the rise in interest for using lumber from different species and the need for an adequate and sustainable supply of raw materials, CLTs from hardwood lumber could be an option to softwood lumber (Grasser, 2015).

In recent years, some significant studies have promoted the use of hardwood lumber for use in CLTs. Aicher (2016) studied three-layered hybrid CLTs built with spruce outer layers and an inner cross-layer of beech wood. The author reported significantly higher rolling shear for hybrid CLTs compared to those made with softwood only. Wang et al. (2015) studied the mechanical properties of hybrid hardwood CLTs fabricated from lumber and laminated strand lumber (LSL). Wang et al. (2015) found that the modulus of elasticity (MOE) was 19% higher. The modulus of rupture (MOR) was 36% higher for hybrid CLTs than the control sample with LSL in the outer layers. Additionally, hardwood CLTs with LSL as the core layer had 13% and 24% higher MOE and MOR.

Kramer et al. (2013) also tested three-layered hardwood CLT panels fabricated from low specific gravity hybrid poplar. They evaluated the bending strength and stiffness of the CLT panels. The results indicated that the MOR of hybrid CLTs was higher than E3-grade CLTs. However, the MOE value was lower than the minimum requirements specified by PRG 320. Mohammad et al. (2015) fabricated three-layer CLT panels using a 6/4-inch National Hardwood Lumber Association (NHLA) grade 2-common yellow poplar lumber. This study concluded that CLTs made from yellow poplar compared well with V1 and V2 grade CLTs with significantly higher stiffness, bending strength, and interlaminar shear capacity.

These studies suggested that hardwood CLTs would be advantageous for structural applications when there is a need for higher stiffness and bending strength. Additionally, hardwood CLTs can solve design problems that require higher interlaminar shear strength. The results from experimental research based on mechanical performance support the concept of using hardwood lumber in CLTs. However, the industrial production of these hardwood CLTs from the existing production system should be evaluated.

Hardwood CLTs for structural applications is an additional material choice for designers and architects. It is also an incredible opportunity for the hardwood lumber market. However, hardwood CLTs' production on a large scale is only possible if manufacturers have information and a willingness to accept hardwood lumber. In addition to manufacturers' acceptance of hardwood lumber as raw material, it is also necessary for manufacturers to have adequate technology to process hardwood CLTs.

Understanding the current practices used in CLT manufacturing and identifying the potential to use hardwood in CLT manufacturing are the first steps toward successful implementation. The current technology used by manufacturers may not be adequate to begin hardwood CLTs production. There must be modification to use hardwood lumber in the current production setup, and work must be done to quantify the scale and level of adjustment needed. Thus, a study is necessary to identify those factors. Therefore, this research aims to study the current manufacturing practices for CLT in North America. This study also aims to record manufacturers' perspectives to identify the opportunities and challenges of using hardwood lumber in CLT manufacturers’ existing setup. The following section includes the methodology used for data collection to complete this research.

3.1 Methodology

A case study method was designed to understand CLT manufacturers’ current practices and their perspectives on using hardwood lumber in CLT panels. Both qualitative and quantitative data on current CLT manufacturing practices were required to answer the research question. A case study is the best instrument to collect a combination of quantitative and qualitative data (Tellis, 1997). Hardwood CLT production is not currently standard practice so, it was necessary to make numerous assumptions and predictions to collect information to answer the research questions. Using a case study methodology allows researchers to gather information beyond quantitative statistical results and helps researchers see the circumstances from the subject's perspective (Zainal, 2007). Tellis (1997) and Yin (2013) argued that the case study approach clarifies the process and outcome through comprehensive observation and analysis, with quantitative and qualitative data from the subject under study.

3.1.1 Case Study Design

This case study was designed according to the theoretical framework proposed by Yin (2013), which includes five main components: research questions, research purpose, unit of analysis, linking data to the research purpose, and criteria for interpreting a case study's findings. Each of these components is discussed in detail in the following paragraphs.

3.1.2 Research Questions

The research questions for this case study were defined as

1) What are the current practices and capacities of CLT manufacturers in North America?
2) What are the manufacturers' perspectives on the potential and limitations of using hardwood lumber in the existing manufacturing setup?
3) What is the production cost of softwood CLTs and how does the cost change with a change in lumber value?

3.1.3 **Research Purposes**

The standard choice of lumber for CLT manufacturing are softwood species. As PRG 320 only recognizes softwood lumber for structural applications, lumber from potential hardwood species is not considered for CLT manufacturing. However, some CLTs producers are using hardwood for manufacturing non-structural products like road mats and crane mats. As higher-grade hardwood lumber is not cost-effective to compete with softwood CLTs, lower-grade lumber is the suitable lumber type for CLT production (Grasser, 2015; Mohamadzadeh et al.,2015).

The CLT standard handbook specifies that CLTs lumber's quality must be surfaced on all sides before applying any adhesive and should contain less than 15% moisture. The lumber should be of uniform dimension and be a minimum of visually graded Number 2 for the load-bearing side (dominant strength direction). Lumber for the primary strength direction must have a thickness to width ratio not less than 1.75. Also, for the non-load-bearing orientation (minor strength direction), visually graded Number 3 lumber with a thickness to width ratio of not less than 3.5 is minimum (PRG 320).

For pallet use, it is not necessary to plane the lumber surface. None of the lumber is kiln-dried, so low value hardwood lumber is not being produced for structural use. Because of PRG 320 requirements, lumber from the current hardwood sawing process requires additional value-added work to prepare the low value hardwood lumber for CLT use. The opportunities and limitations of using low value hardwood lumber in commercial CLT production in existing production practices have not been explored yet. Thus, the purpose of this study is to measure possible opportunities and identify hindrances of using hardwood lumber in CLTs from the perspective of CLT manufacturers.

3.1.4 **Units of Analysis**

The scope of this case study was limited to North America. At the time of the survey, there were only six CLT manufacturers - four in the US and two in Canada. The research team contacted all six CLT manufacturers. Neither CLT manufacturers in Canada agreed to be interviewed. Only three of the four CLT manufacturers in the US agreed to participate.

3.1.5 Data Collection

The primary data collection methods were face-to-face interviews (FTFI) and facility visits. This research satisfied the minimum conditions mentioned by Mathers et al. (2007) to choose FTFI as the data collection method. Mathers (2007) suggests that FTFI is more appropriate and can yield a better result if:

- the subject matter is vague to the respondent, and questions need to be coded
- the questionnaires are likely to be lengthy, and participants are expected to respond to all questions
- the research is being carried out with a limited number of participants
- the subject matter under investigation requires qualitative data with open-ended questions

This research meets most of the conditions above, so FTFI was used as a data collection instrument. The use of hardwood lumber in CLT manufacturing is a new concept. The language used in production is not well defined. Hence, the survey questions needed to be worded carefully, and each respondent needed to understand the intent of the question. Therefore, most of the questions in this case study required further clarification to get a quality response.

All three facilities were visited, and the company representative was interviewed at the time of the visit. One manufacturer allowed the visit before the interview process. The other two companies scheduled the tour following the completion of the interview. The research team had the opportunity to follow up on each question to understand the manufacturers' current practice. The information collected during the plant tours was used to supplement the interview process or clarify the data collected if the visit was after the interview process.

3.1.6 **Questionnaire Design and Purpose**

The interviews were completed with standard sets of questions for all CLT manufacturers. The final interview questions were prepared and finalized by the research team and approved by the Internal Review Bureau (IRB) of Virginia Tech. A collection of twenty-seven questions was designed to address the research questions. Specific questions were developed for production capabilities of, current practices of raw material acquisition, and preparation. Questions were also designed to measure the supply chain practice, manufacturing process, maintenance, and quality control to document CLT manufacturers' current practices. Additional questions were designed to understand the opportunity for using hardwood lumber as raw materials. Lower-grade lumber from hardwood graded as NHLA 2 Common and lower was presented as a significant source in CLT manufacturing to record the manufacturer's perspective.

Questions were developed to gather information from manufacturers regarding the scale and level of the modification required if their existing technology was not adequate to process hardwood lumber. Questions were also designed to help understand the opportunities for continuous collaboration between hardwood sawmills and CLT manufacturers to manufacture lower-grade lumber as ready to use raw material. Finally, sawmills were asked about production cost to manufacture softwood CLTs based on cost factors defined by FPInnovations (2011). Manufacturers were asked to provide the hardwood CLTs' production cost with the current setup when using NHLA grade 2 common and lower-grade hardwood lumber. The questionnaire used for the interview process is attached in Appendix A.

3.1.7 **Data Validation**

This research was completed using both qualitative and quantitative data collection. The validation of the participant's response with qualitative data was crucial to obtain accurate information. With the FTFI method of data collection, validating the answers was the most critical factor. In qualitative research, findings must reflect the existing situation and be supported by definitive evidence (Triangulation, 2014). The most widely used approach for validating qualitative research is data triangulation (Barbour, 2001).

The interview tool developed asked the same questions of all participants. Additionally, while interviewing the participants, the same question was asked multiple times to the participants in similar contexts, with various follow up questions, to cross-check the answers (Triangulation, 2014). Some of the information collected was verified with secondary sources, if available in the literature.

3.2 Observation and Results

Two members from the research team, comprised of one Ph. D. student and four committee members, visited three of the four CLT manufacturers in operation at data collection time. Each manufacturer was asked the same set of questions prepared by the research team. Follow up questions were asked by the visiting members to obtain an accurate response to each question based on the manufacturer's practice. The observed results are discussed in the following four sections.

3.2.1 Status and Practice of CLT manufacturing

The companies' demographic information and current practices are summarized in Tables 3-1, Table 3-2, and Table 3-3. Table 3-1 highlights the demographic data of the participating industries. The production efficiency and inventory capacity are presented in Table 3-2. Table 3-3 summarizes the manufacturers' existing supply chain practices, company policy for dealing with non-conformity, the company's practice of using a combination of the species, and the level of collaboration with lumber producers.

The productivity of each company is dependent upon the efficiency of the equipment and technology adopted. The material or process that can limit the production capacity is identified as the bottleneck equipment or process for the production line. At present, the press is the bottleneck for most CLT production lines because it is time-sensitive and a comparatively more time-consuming process. The production volume of the CLT for structural applications is less than 50% for the two companies. One company does not produce any structural grade CLTs. When these companies begin full-scale production of structural grade lumber, it will be clear, which is the current setup's bottleneck process and instrument.

Table 3-1: Introductory information on CLT manufacturers interviewed for this study.

Company	*A*	*B*	*C*
Number of mills	1	1	1
Wood species used	SPF No. 1/No. 2	SYP/Douglas-fir/ SPF	SYP No. 1/No. 2
Maximum press capacity(psi)	1000	1000	1000
Maximum format (m x m)	2.4 x 12	3.5 x 12	3.5 x 12.2
APA- certified	Yes	No	Yes
Production capacity (m3)	75,000	350,000	188,000
Automation in production lines	Semi-automated	Highly automated	Semi-automated
number of presses	1	3	1
Structural grade CLTs (%)	38	0	40
CLTs grade	V3/V4	V3	V3 and E4 in plan

Those companies with experience using hardwood lumber stated that this required higher press capacity and slightly longer pressing time than softwood lumber. All companies have a press with the ability to press up to nine plies (five layers in one direction alternating with four layers in the CLT's perpendicular direction). Two of the manufacturers were built to manufacture 60-feett-long panels. One can produce 52-feet-long panels, but CLTs' current production is limited to the maximum length of 40 feet due to limitations in transportation for larger boards.

Table 3-2: Production efficiency and inventory capacity of participating companies.

Company	*A*	*B*	*C*
Efficiency Based on Lumber Consumption	70%	98%	88%
Effectiveness Based on Machine Utilization	45%	85%	50%
The Bottleneck of the Production Line	Press	Press	Press
Lumber Inventory (MMBF)	500	90000	One-week consumption volume
Finish Goods Inventory	One-week production volume	600,000 panels	One-week production volume

Table 3-3: CLT manufacturers' policies of the raw material supply chain and non-conformity.

Particular	*A*	*B*	*C*
Dedicated lumber suppliers	No, receives raw materials from various suppliers within a 200-mile radius	Limited, but receives raw materials within a 100-mile radius	Three suppliers in a 50-mile radius and working for more
Receiving ready to use lumber	Most of the time	Yes, if not, return to suppliers at their cost	Most of the time
Major non-conformity	High moisture content	High moisture content	High moisture content
Handling non-conformity	Re-work to match the minimum requirement	Return to suppliers for major non-conformity	Return to suppliers for major non-conformity
Additional value-added work	Surfacing, air drying, trimming, regrading	Air drying (if required), surfacing, trimming	Air drying, surfacing, trimming, regrading
The dedicated line to work on non-conformity	Yes	No	No
Used combination of lumber species	Yes	Used to but now stick with single species	No
Collaborates with lumber producers	No, but with some suppliers to supply a limited volume of lumber	Yes, for softwood, but not enough to meet the capacity	In the process and has a policy to receive the raw material from limited suppliers
Current collaboration	Drying	Supplying ready to use lumber	None

3.2.2 **Hardwood Lumber to Produce CLTs**

Two manufacturers had used hardwood lumber in CLT panels in the past. The customers' demand guided the practice of using hardwood, and both CLT manufacturers produced the panels as a customized product. All of the hardwood CLTs produced by the manufacturers were non-structural grade CLTs for use as crane mats. When the research team visited the manufacturing facilities, both manufacturers used only softwood lumber to fabricate CLT panels. Both companies would manufacture hardwood CLTs if, and only if, there was significant and constant demand for the product. During our visits, neither company had an order for hardwood CLTs. The only request for hardwood CLTs was for mats used in the oil and gas industry.

Company A produced seven-ply CLT panels with five softwood lumber layers in the middle and a hardwood lumber layer on the top and bottom. This company used mixed hardwood species that included beech, hickory, maple, and other species provided by the customer. The company manufactured multiple batches of CLTs using mixed species of hardwood lumber. Based on these experiences, the company identified the following problems when using hardwood lumber in CLT panels:

1. The lumber's inventory of various dimensions (length, width, and thickness) significantly decreased productivity.
2. Most of the lumber was not dried to below 15% moisture content. This company received the lumber from the end-use customer, so they had to dry the lumber to meet the minimum moisture content before using it for CLT manufacturing. Hardwood dries at a slow pace, so it was challenging to produce the CLT panels in the scheduled timeframe. The company had to rely on air drying the lumber. Since it required extra work at the manufacturing facility, the manufacturing cost was higher than regular production.
3. Using multiple lumber species in the same layer in CLT production impacted material handling efficiency. It required additional sorting of lumber by species to avoid applying excessive pressure on low-density lumber during the bonding process.
4. Some hardwood lumber was significantly harder on cutting tools. The production process had to be halted numerous times due to the dulling of tools.
5. Some of the hardwood dust was caustic to employees, causing respiratory issues.
6. The press time for hardwood CLTs was longer than for softwood CLTs.

The second company had used both hardwoods only and a combination of hardwood and softwood lumber in making CLT panels. This company collected lumber from different hardwood species from the region, including red oak and white oak, with various thicknesses, lengths, and random widths. However, that caused multiple problems during the production process. The company reported the following issues using hardwood lumber:

1. Manual pre-sorting of the lumber based on length, thickness, and width was the biggest problem for the highly automated production line.
2. The company did not have finger joint capacity, so it was challenging to collect similar length lumber. The company trimmed each piece of lumber to a specific length. Lack of finger-joint technology increased wood loss and reduced productivity.
3. Surfacing the lumber on all four sides was the most complicated process due to the lumber's various widths and thicknesses.
4. Almost all the lumber had higher moisture content and needed to be dried to below 15%.
5. Due to the variation in the raw material dimensions, the company had to build supplemental production lines. These production lines were used as a bypass to the main production line. The lumber of different thicknesses and widths was sorted. This lumber was pulled into the process by the operator if they found non-conformity layers. This practice caused multiple interruptions in the production process, which reduced productivity and required two additional employees on the production line.
6. The press time for hardwood CLTs was longer than softwood CLTs.

Company B used polyurethane as the adhesive. The company worked together with the glue manufacturing company to test polyurethane on lumber with different moisture contents. It performed well on hardwood lumber and hybrid CLTs made of hardwood and softwood lumber in their experience. They found that polyurethane worked well on hardwood lumber with a moisture range of 7% to 25% and produced a significantly strong bond. The company mentioned that a hardwood-softwood combination in the CLT panels yielded a considerably higher bond strength. The observed shear strength for the softwood-hardwood hybrid CLT panels was, on average, 1000 psi, and, for all tests carried out, there was a 100% wood failure.

Company B reported that the shear strength was observed between 600 psi to 800 psi using a similar manufacturing and shear strength test for softwood CLT panels. For all the experiments carried out, there was an 85% to 100% wood failure. These results suggest that hardwood-softwood CLTs bonds were more robust and performed better when compared to softwood CLTs.

Company B also reported transportation problems for delivering hardwood CLT panels to the construction site. Hardwood species suitable for CLT applications have a higher density than softwood species. The cost of transportation for higher density materials increased for the same number of CLT panels, ultimately impacting the project's overall cost. For a large project, it would be necessary to consider transportation costs, given the additional weight. The company estimated that the hardwood CLT panels they produced required 40% more trucking cost than softwood for the same volume of panels.

Both companies were optimistic about markets for hardwood CLTs. Company A believed that there would be demand for hardwood CLTs on an industrial scale in the next ten years. Company A strongly believed that the CLT market would flourish in the coming days and that there would be the opportunity to use hardwood lumber as raw material to provide variation in CLTs for structural applications. Both companies believed that adequate supplies of structural grade hardwood lumber would be the market's primary driver in the future. Company A saw opportunity for hardwood lumber's to produce hybrid CLTs with softwood and gradually move toward hardwood only CLTs if the market witnessed significant demand. Additionally, both companies suggested promoting hardwood lumber as a CLT raw material combined with softwood; it would be necessary to document hardwood – softwood CLTs' performance tests and provide the results to the stakeholders.

3.2.3 **CLT Production Cost**

In the CLT business, the production cost is defined as the total cost from design to installation. The most significant elements were the raw material cost, which includes the cost of lumber and adhesive. However, other multiple factors contribute to the actual cost of CLT production. If the available lumber needs additional value-added work at the CLT mill like drying, dressing, trimming, and ripping, the production cost goes up.

Production technology adopted by the company was identified as another significant cost factor. All companies suggested that a highly automated production line had lower production costs than semi-automated and manual production lines. So, all manufacturers were continuously working to increase automation of the production line. The capacity of the press was reported as another factor that significantly contributes to CLT production cost. Press time was reported as the function of open time after applying adhesive on the lamella surface. Open time is defined as the time taken to apply adhesive on the lamella surface before pressing starts. So, as the open time increases, press time also increases. The standard practice for all companies was to press panels for a minimum of three times the open time. Hence, a single minute increase in open time required an additional three minutes of press time.

Based on the technology adopted by the company, another cost factor was identified as CNC machining. CLT panels are manufactured as a part of the structure. Each panel is manufactured for a unique position on the structure. CLTs were processed through CNC to allow the necessary work on that panel, based on the panel's location in the structure. Some of the significant CNC work on boards includes trimming, ripping, drilling, and cutting duct lines for utility access. Thus, CLTs that required a minimum of CNC work also have a lower production cost and vice-versa. Production cost also depends on the company's location and the CLT construction site. Transportation and installation are part of the total production cost. The installation cost becomes a significant factor if the structure's construction site is far away due to transportation costs.

Most CLT panels are customized products depending upon the end-use, so the production cost per cubic meter of CLTs is different from batch to batch and project to project. It is hard to generalize the production cost of CLTs from design to installation based on various projects. So, the companies were asked to share the production cost by different cost factors, as identified by FPInnovations (2011). The general distribution of CLT production cost for both mat CLTs and structural grade CLTs by the cost factor is summarized in Table 3-4, based on the information provided by various industries.

Table 3-4: Average CLT production cost using SYP lumber based on various cost factors

Categories	*CLTs mat*	*Structural CLTs*	*FPInnovations*
Wood	75%	40%	53%
Adhesive	6%	5%	8%
Labor	6%	5%	15%
Energy/fuel			2%
Packaging			1%
Shipping			2%
Equipment maintenance	13%	50%	3%
Financial expenses			11%
Others			5%

Research on hardwood CLTs in recent years has raised concerns about production cost. It was assumed that hardwood CLT's production cost was significantly higher than softwood because of the per-unit lumber cost. The estimated cost of structural grade hardwood CLTs using one manufacturer's identical production setup is presented in Table 3-5. The cost per cubic meter for the CLT was calculated by adjusting only the lumber's buying cost and comparing it with softwood CLTs. This cost estimation is based on per cubic meter of CLT production without the architectural design. The softwood lumber's buying cost was assumed to be $300 per MBF and $450 per MBF for hardwood lumber.

The production cost variation with the CLT layer change is due to the press's fixed height. When the number of layers increases in each panel per single press time, the number of panels decreases for that batch. The company reported manufacturing 6, 4, 3, and 2 panels at once when 3-ply, 5-ply, 7-ply, and 9-ply panels were pressed in a batch, respectively. The company suggested that it was economically beneficial to produce 5-ply CLTs with their current setup, which is evident when looking at the estimated production cost.

Table 3-5: Production cost of one cubic meter of structural grade SYP and hardwood CLTs using the CLT manufacturer's existing setup with lumber costs of $300 and $450 per mmbf, respectively.

CLTs layers	*Softwood CLTs ($)*		*Hardwood CLTs ($)*		*Percentage change*	
	Min	Max	Min	Max	Min	Max
3ply	700	780	820	945	17%	21%
5ply	615	690	690	790	12%	14%
7ply	705	775	810	915	15%	18%
9ply	710	820	820	985	15%	20%

3.2.4 **Drivers and Challenges of CLT Manufacturing**

CLT manufacturing industries are in the learning and doing stage, as the industries have just started production at a commercial level. Cross-laminated timbers, as a new product and new industry, has significant challenges and opportunities. All three industries were asked to identify the challenges and drivers of softwoods and hardwood CLTs. The response collected from all three manufacturers to use softwood lumber is summarized in Table 3-6.

Table 3-6: Challenges and drivers identified by CLT manufacturers using softwood lumber.

Particular	*A*		*B*		*C*	
	Challenges	Driver	Challenges	Driver	Challenges	Driver
Raw Materials	▲			▲		▲
Technology		▲		▲		▲
Suppliers	▲			▲		▲
Partnerships		▲		▲		▲
Education	▲		▲		▲	
Markets		▲		▲		▲
Financing		▲		▲		▲
Labor	▲	▲		▲	▲	
Regulations	▲		▲		▲	
Sample number	2					

For Company A, softwood lumber available in the region frequently needed additional work that included drying and dressing in CLT use preparation. So that company identified currently available raw materials as a challenge because it increased the production cost. Company A did not have dedicated lumber suppliers, which was identified as a challenge. The awareness and education of CLT construction were identified as challenges for all companies. All companies agree that there was a shortage of qualified technicians and operators. Each company was looking forward to implementing training and other job enhancement programs to meet such demands. Also, two companies reported working together with educational institutes to meet a similar workforce's growing demands.

The responses obtained from the manufacturers to identify the drivers and challenges for hardwood CLT manufacturing are presented in Table 3-7. The raw material availability was identified as a challenge in using hardwood lumber. Both manufacturers reported low value hardwood lumber graded as 2 common and below was potential raw material, due to the higher value of superior grade lumber. Both manufacturers also agreed that the low-value hardwood lumber's available volume was high within an acceptable radius to obtain raw materials. However, this lumber was mixed species and needed significant value-added work to prepare it for CLT applications.

Both manufacturers suggested minimal or no communication with hardwood sawmills to acquire hardwood lumber. There was a lack of information sharing of the raw material's specific requirements between hardwood lumber producers and CLT manufacturers. One of the common reasons CLT mills avoided contacting hardwood sawmills to produce ready to use lumber for CLT application was the minimal demand for the lumber. Both manufacturers required a limited volume of lumber for a project and were not sure about future demand. On the other hand, hardwood sawmills were unaware of this potential market. None of the CLT manufacturers had requested that hardwood sawmills produce ready to use hardwood lumber for CLT application. Company B had suggested that it was cheaper for them to prepare the lower grade lumber available in the market compared with buying ready to use lumber from a sawmill. As a result, low-grade lumber from hardwood sawmills was being produced to meet industrial-grade lumber requirements. This low-grade hardwood lumber was sold as pallets and used for other industrial products. None of the hardwood sawmills produced low value hardwood lumber specifically for CLT application, so these mills were not meeting the raw material specification in PRG 320. There was not much information on their capabilities for producing lumber for CLT application.

Table 3-7: Challenges and drivers of using hardwood in CLTs

Company	*A*		*B*		*C*	
	Challenges	Driver	Challenges	Driver	Challenges	Driver
Raw materials	▲		▲			
Technology	▲		▲			
Suppliers	▲		▲			
Partnerships		▲		▲		
Education	▲		▲		No experience	
Markets		▲		▲		
Financing		▲		▲		
Labor	▲			▲		
Regulations	▲		▲			
Sample Number	2					

Education was identified as a limiting factor for CLT manufacturers in two respects. The first was the lack of formal training and workshops for the CLT mill operators, making it challenging for CLT manufacturers to find qualified technicians and other employees. The second was a lack of education, which would increase awareness about the CLT system's capabilities and advantages. All three participants agreed that many potential consumers were not educated about CLT construction's additional benefits as an existing construction material. Lack of awareness by the public and potential customers was identified as a challenge for CLT construction. The current technologies to manufacture softwood CLTs were recognized as inadequate to process various hardwood species by manufacturers. Some of the processes are caustic and hard on tools, causing multiple breakdowns in production.

The cost of the CLT manufacturing system was not identified as a challenge by the manufacturers. Most of the projects completed or in the construction phase using structural grade CLTs were supported by federal or local governments to promote CLT construction systems. The manufacturers were confident that, when people became more aware of CLT construction's advantages, market growth would not be limited by the associated cost.

Additionally, if CLT production were to move to an industrial level, manufacturers were confident that the production cost would be lower, making CLT panels more competitive. Existing regulations in the US construction industry were identified as another challenge to market adoption of hardwood CLTs because the standard code excludes hardwood lumber for structural applications. Possible collaboration with other CLT manufacturers, lumber producers, and suppliers was recognized as a primary driver by all three manufacturers for promoting hardwood CLTs. Additionally, current market opportunities for CLT were also identified as the primary driver for hardwood CLTs.

3.3 Discussion and Conclusions

This study indicates that CLT manufacturers' efficiency is decreased because of the additional value-added work that needs to be performed on lumber transported to CLT mills. At present, using softwood lumber still requires extra work that includes drying to the proper moisture content, trimming, and surfacing before applying glue. For example, one company reported that for 100 lumber deliveries of softwood lumber, less than 90 deliveries passed the required moisture content test. The other ten deliveries required additional drying at the facility or were removed for alternative use. If CLT manufacturers could receive ready-to-use softwood lumber, productivity would increase significantly. Collaboration with lumber producers was discussed as a possible solution to avoid additional value-added work of CLT mills. At present, there are few collaborations between CLT mills and lumber suppliers in the US.

All participants in this study indicated using hardwood lumber as raw material required some modification in their current production process. Neither manufacturer saw problems in manufacturing HCLTs in their production line. Both manufacturers were confident in the ability of their technology to work with hardwood lumber. These manufacturers have no issues using hardwood lumber in finger jointing, adhesion, pressing, and CNC machining. However, the CLT mills reported longer press time, and that some hardwood lumber species dull the cutting tools more quickly. Manufacturers suggest replacing their cutting tools with a more robust tool to use hardwoods.

All CLT mills agreed that using currently available hardwood lumber in CLT manufacturing could negatively impact the industry's productivity. The overall efficiency of the CLT mill when using softwood lumber is approximately 70%. Using non-structural grade lumber as a raw material in the existing system would require additional value-added and material removal work. Extra value-added work requires more resources that would reduce the productivity of the mill. Thus, non-structural grade hardwood lumber does not exhibit additional raw material opportunities with the current manufacturing system.

This study has shown lumber value as the significant cost factor in CLTs production. On average, 40% of the participating CLT mills' CLT production cost is lumber value only. Both labor and adhesive account for 5% each of the total CLT production costs. The remaining 50% of the total CLT production cost is included in the design, transportation, installation, and other factors. These results help to conclude that raw material cost is a significant factor in CLT production cost. For the use of hardwood lumber in CLTs, the lumber value of the species chosen for use as lamella determines the total production cost.

One of the participating companies had evaluated the production cost of the CLT based on different lumber values. The cost information provided for the softwood lumber was $300 per 1000 bf. The observed production cost for a cubic meter of the finished CLTs ranges from $680 to $770. The production cost determined was based on the required value-added work to produce the CLT panel as a finished product for end-use. The same company reevaluated the hardwood CLTs' production cost by adjusting only the lumber value to $450 per 1000 bf and reported the production cost ranges from $780 to $910 per cubic meter. The hardwood lumber value average was $450 per MBF based on the averaged value of 2 common and lower grade lumber from species considered for primary cost evaluation.

These results suggest a 50% increase in the lumber value increases the total CLT production cost by 20%, assuming all other factors remain the same. This estimation did not consider the additional work required to prepare hardwood lumber for CLT use. So, the critical observation from these results is whether hardwood sawmills can produce SGHL at competitive lumber values with softwood lumber or not. Also, it is imperative to determine the share of the other costs when substituting hardwood lumber. Hardwood CLTs can be competitive with softwood CLTs given its unique aesthetic opportunity and a higher strength value provided the production cost remains competitive.

The primary concern expressed by the CLT manufacturing companies was the availability of hardwood lumber in the required quality and quantity within the supply chain radius. The management believed that many hardwood sawmills would have to work together to meet the lumber demand. For example, the mill producing CLTs mats required 150 MMBF of lumber on average for a single project. This demand would be beyond any hardwood lumber producer's capacity unless the company decided to produce only structural grade hardwood lumber. Producing only structural grade hardwood lumber would not be an economical choice for hardwood sawmills, as higher-grade lumber has a significantly higher value.

In addition to the lumber volume, hardwood lumber should be of structural grade-standard. The lumber should be of uniform dimensions, surfaced on all four sides, and dried to below 15% moisture content to avoid extra work and cost at the CLT mill. The randomness in width and various thicknesses of the lumber is a significant problem for CLT manufacturers. There is a considerable wood loss to prepare lumber with random widths, which increases production cost. Also, for a CLT manufacturer that includes finger jointing of lamellas, various lumber length increases the cost. Worst case, for a CLT mill that does not do finger jointing, it would be challenging to find the uniform hardwood lumber length needed to produce CLTs.

All participants interviewed for this case study agreed that the production of structural grade hardwood lumber is essential for successfully implementing hardwood CLTs at the commercial level. At the same time, some agencies have developed rules for grading hardwood lumber for structural applications.

Agencies that had designed grading rules for hardwood lumber for structural applications are Northeastern Lumber Manufacturers Association (NELMA), Northern Softwood Lumber Bureau (NSLB), and Western Wood Products Association (WWPA). None of the hardwood sawmills are currently producing lumber using these rules. Hardwood sawmills must adopt grading rules to produce structural grade lumber to meet the CLT manufacturers' needs.

Even with all the challenges of using hardwood lumber in CLT panels, manufacturers are optimistic about using more hardwood as a raw material. First, CLT mills are looking for a sustainable supply of ready to use raw material. There is a surplus of hardwood lumber, given the contraction of the hardwood lumber market. Second, as CLT's use in construction continues to grow, there will be rising competition for softwood lumber between the traditional and CLT markets. This competition can provide opportunities to use hardwood lumber for structural applications.

For successful hardwood lumber use in the CLT market, the first step will be informing hardwood lumber producers about the opportunity. It is necessary to encourage the hardwood industry to change its practices to manufacture structural grade lumber that meets the APA/ANSI PRG 320 standard. There is even more potential if hardwood sawmills focus on producing structural grade material from low value logs. Finally, a collaboration between hardwood sawmills and CLT manufacturers is an essential factor in solving potential problems. Some specific hardwood log species have similar mechanical and physical properties as softwood lumber. Hardwood sawmills and CLT manufacturers could collaborate to explore lumber's performance from these species in the CLT application. The results from such collaborations will be significant for the future use of hardwood lumber in CLT manufacturing.

Thus, this study concludes that CLT mills have the technology to use hardwood lumber, but for commercial use of hardwood, the first step is to manufacture structural grade hardwood lumber of CLT raw material of the required quality and volume.

3.4 Summary and Major Findings of the Study

The research team visited all three CLT manufacturers between June and September 2019. Based on the research team's observations, the study results can be summarized in the following points.

1. Structural grade CLTs and CLT mats are the standard product for CLT manufacturers in the US. At present, CLT mats comprise approximately 74% of the total production volume.
2. The production efficiencies of CLT manufacturers are, on average, 84% based on lumber consumption for the manufacturers considered in this study, where productivity was based on machine utilization averages below 70%.
3. The lumber species common to all CLT mills is southern yellow pine (SYP). However, manufacturers have considered using other softwood species and groups like Douglas-fir, Larch, the Spruce-Pine-Fir (SPFs) group, and the Hem-Fir group.
4. On average, 40% of production cost is the lumber value when CLTs are produced from SYP lumber. Both labor and adhesive account for 5% of the total CLT production cost, and 50% of production cost comes from design, transportation, installation, and other factors.
5. When lumber value at the current production line increased by 50% for a CLT mill, the production cost increased by 20%. If the lumber value difference between softwood and hardwood species remains below 50%, CLTs' production cost remains below 20%, provided other costs stay the same.
6. Two of the CLT manufacturers have used hardwood lumber in CLTs for specific projects and had positive experiences with the performance. The hybrid CLTs, a combination of softwood and hardwood lumber tested for performance, yielded higher strength than softwood CLTs.
7. The problems in using hardwood lumber in manufacturing CLTs included the various dimensions of the lumber available in the market, limited suppliers, and insufficient lumber volume for a species or group of species. Additionally, some hardwood lumber is hard on tools prompting multiple breakdowns. Some hardwood species are caustic, causing health problems for employees.

8. In comparison to softwood CLTs, hardwood CLTs of similar dimensions and layers have higher transportation costs. The increased weight of hardwood CLTs due to higher specific gravity and its impact on trucking weight limits can be the primary variable cost in larger projects.
9. From manufacturers' perspectives, there is an increased potential to use hardwood in CLTs. However, it depends on the volume of lumber that matches the minimum specifications of the CLT standards.
10. Some manufacturers are interested in collaborating with hardwood lumber producers to promote increased hardwood lumber use in CLTs. For commercial use, CLT mills need a guarantee of a minimum volume of lumber.

CHAPTER 4. PRODUCTION OF STRUCTURAL GRADE HARDWOOD LUMBER

4 Introduction

Hardwood sawmills produce appearance grade lumber because it is primarily used for cabinet design, furniture, and flooring. Sawmills are using various technologies to manufacture lumber and other products, and there is a high level of discrepancy in hardwood sawmill operations in the US (Cumbo, 2006). Sawmills adopt technology and operational practices based on the market. Most US hardwood sawmills are family-owned and small, with an annual production capacity of less than 1 million bf (Cumbo, 2006). Many of these small sawmills produce lumber from limited hardwood species for local markets. Only a few sawmills are manufacturing a significantly larger volume of lumber from different hardwood species.

The great recession did great harm to the hardwood sawmill industry. Many hardwood sawmills were shut down or were sold due to new complexities in operation caused by increased internal and global competition (Parhizkar et al., 2009; Espinoza et al., 2011). The business agility of sawmills continuously deteriorated as the log and stumpage values continued to increase. Lumber value decreased due to stiff competition (Luppold et al., 2014). The impact of the recession caused the furniture and cabinet industries to move offshore. They were the primary consumers of hardwood lumber (Parhizkar et al., 2009; Espinoza et al., 2010; Luppold et al., 2014). The market's change created an excess supply of lumber for a limited market and prompted increased customized demands from the end-user (Espinoza et al., 2011). Reduced lumber demand and increased competition required sawmills to produce small lumber of various species, grades, and thicknesses to meet customized demand (Espinoza et al., 2011; Luppold et al., 2014). These customizations significantly decreased the efficiency of sawmills' operations. They narrowed the profit margin, which led to a loss of revenue (Johnson, 2009). Hardwood sawmills remain in business with minimal or no profit following the great recession, hoping that there will be a sustainable market soon (Johnson 2009; Parhizkar et al. 2009, Espinoza et al. 2010, Luppold et al. 2014).

For years, the domestic market for hardwood lumber continued to have problems after the great recession of 2008-2009. In the absence of a sustainable domestic market, hardwood sawmills explored the export market. China and other Asian and European countries were buying hardwood logs and lumber from the US. However, the export market also hit rock bottom in 2019. The American Hardwood Export Council (2019) estimated that by July 2019, exports of US hardwood products were down by $494 million compared to July 2018. The decrease in exports was mainly due to China's tariffs on forest products and created an oversupply of hardwood logs and lumber in the US (Pryor, 2019).

In addition to the limited market, another problem faced by hardwood sawmills is the continuously increasing volume of low value logs in the sawmill inventory (Cumbo et al., 2003; Luppold et al., 2019). The increased volume of lower grade logs in the inventory worsens the financial wellbeing of sawmills. Luppold et al. (2019) estimated a 19% increase in low-quality saw timber-sized hardwood trees in 2017 from 2008 in the forest inventory of the US's northeastern region. An increased volume of lower grade lumber needs an additional market beyond the existing market because the market for lower grade hardwood lumber has been saturated in recent years (Buehlmann et al., 2017). The majority of low value hardwood lumber is being used as raw material for pallet production (Buehlmann et al., 2017). A total of 8.81 billion bf of hardwood lumber was used in the US in 2018, and 53.1% (about 4.68 billion bf) of that hardwood lumber was used as an industrial product (Caldwell, 2018). Caldwell's (2018) report also indicated that 36.7% (1.72 billion board feet) of industrial-grade hardwood lumber was used in the pallet industry. Railway ties accounted for 12.2% of the industrial-grade lumber, and 4.2% were used for board roads or mat timbers. Industrial grade lumber has minimal return for hardwood sawmills so that the alternative market could attract many hardwood mills.

A new market opportunity for oversupplied and low value hardwood could be to use it as raw materials for mass timber construction (Grasser, 2015; Quesada, 2018). The CLT industry is a new and exponentially growing market in the US. The Beck-Group (2018) estimated that CLT demand would be 515,400 m3 by

2025, which would require approximately 3.9 billion bf of nominal lumber. Hence, CLT manufacturers must find alternative sources or products to meet the increasing demand. CLTs from low value hardwood lumber provides an excellent opportunity to expand the hardwood lumber market. Using low value lumber in CLTs requires additional value-added work. The CLT mill survey from Chapter 3 of this research indicates that CLT mills are looking for both quantity and quality of SGHL for CLT application.

Two US-based CLT manufacturers have used hardwood lumber available on the market. Both manufacturers were optimistic about the performance of hardwood lumber for CLTs. The major limiting factor reported was variation in the dimensions of hardwood lumber available on the market. Various thicknesses, widths, and lengths of the lumber increase the material handling and lamella preparation cost. Another major problem reported for hardwood lumber as raw material was the moisture content of the lumber. Most of the lumber received by both CLT producers needed additional drying in the CLT mill to meet the minimum requirement of CLTs lamella. With increased production time and expenses, the use of hardwood lumber significantly reduced production efficiency.

Hardwood sawmills are unaware of this new market opportunity because CLT mills have not communicated the need. CLT mills were using hardwood lumber for non-structural applications such as road mats and crane mats. CLTs for non-structural applications did not require meeting PRG 320 specifications and used lumber commonly found in the market. However, if hardwood lumber is to be used in CLTs for structural applications, it needs to meet the PRG 320 standard. Matching quality and quantity of the SGHL for CLT application may need multiple adjustments in sawmill operations. Sawmills must see the new market as an economically and technically feasible process and a sustainable opportunity. Thus, this study addressed an important need to understand the status and opinion of hardwood sawmills regarding the production of SGHL from potential hardwood species.

Information on sawmill production capacity, sawn species in the sawmills, lower grade lumber production volume, and hardwood lumber's production cost is critical to measure a sawmill’s status. Sawmills' capabilities to efficiently saw standard width lumber, surface all four sides, and kiln-dry to the 15% and lower moisture content are necessary for producing SGHL. For a sawmill, the expected minimum annual demand for new products should be met to begin producing SGHL. New products beyond the existing market must show equal to or higher returns than traditional products. Sawmills' willingness to collaborate in production, marketing, and investment is pivotal to begin SGHL production. Sawmills might need to upgrade existing technology or need to expand their current capacity to begin SGHL production. Therefore, it was necessary to measure the degree of adjustments needed by sawmills and their willingness to invest in those necessary changes.

The structural grade lumber market is growing and cannot meet US domestic demand. With the growth of the CLT market, structural grade lumber demand is growing exponentially. Hardwood sawmills need additional markets but only produce appearance grade lumber that needs additional value-added work for structural application. Production of SGHL from potential hardwood species could solve these problems for hardwood sawmills and reduce structural grade lumber imports. So, sawmills may need to adjust their production strategies and adopt all possible adjustments that may demand additional investment and resources. Thus, this study's scope was to map the hardwood sawmills' status and observe its current ability to produce SGHL. This research collected information on the existing practices of hardwood sawmill operations in the US to identify the sawmills' fundamental limitations and capabilities. The information on value-added work required to prepare SGHL for CLT application was necessary to identify and quantify the changes or modifications required to existing sawmill practices. Thus, this study's objective was to measure hardwood sawmills' status to produce SGHL from low-value logs.

4.1 Methodology

A survey study was chosen as the instrument to map the current capacity, limitation, and production status of hardwood sawmills. Surveys are a widely accepted method to map the status of the study subject. The survey helps for a more precise sampling focused on drawing valid conclusions and supporting decision-making. Additionally, surveys are more useful for understanding a large population (Allen et al., 2011). The response from a survey is more balanced and reflects candid and valid answers to questions. The anonymously conducted survey provides an opportunity for more authentic and explicit replies than other research methodologies (Groves et al., 2009). Industries are sensitive to their personal information, so the anonymous survey can be an opportunity to obtain fact-based data (Dillman et al., 2009). The data collection instrument's cost is also a significant factor in the research, and the survey study has the lowest cost compared to other methodologies for a large sample size.

A survey also may enable the ability to gather demographics data, sawmill's views on new products and markets, and hardwood sawmills' needs to begin producing new products. Case studies and model-based methods best describe the scenario of the subject under scrutiny. For a subject like sawmills with higher technology and operations discrepancies, the case study and model-based method have an equal chance of excluding most practices in other sawmills. A survey study has the flexibility to adapt variations in a study subject and the response. The objective to map the status of sawmill operations and the operator's willingness to adopt a new product in existing production lines will help communicate the current ability and limitations of sawmills to produce SGHL.

4.1.1 Data Collection Method

There are two different data collection procedures for survey research: qualitative and quantitative (Allen et al., 2011). Qualitative data are not common in survey research unless the sample size is minimal. Most survey research uses a quantitative approach. Stevens (1946) classified the quantitative data collected from survey research into four scales: nominal scale, ordinal scale, interval scale, and ratio scale. This survey was completed by collecting responses primarily using the nominal scale. The survey study's significant components are the sample selection and the questionnaires' design, discussed in the following paragraph.

4.1.2 **Sample Selection**

The scope of this study was to measure the current ability of hardwood sawmills to produce SGHL. Sawmills from the highlighted states in Figure 4-1 were the sample pool for the survey.

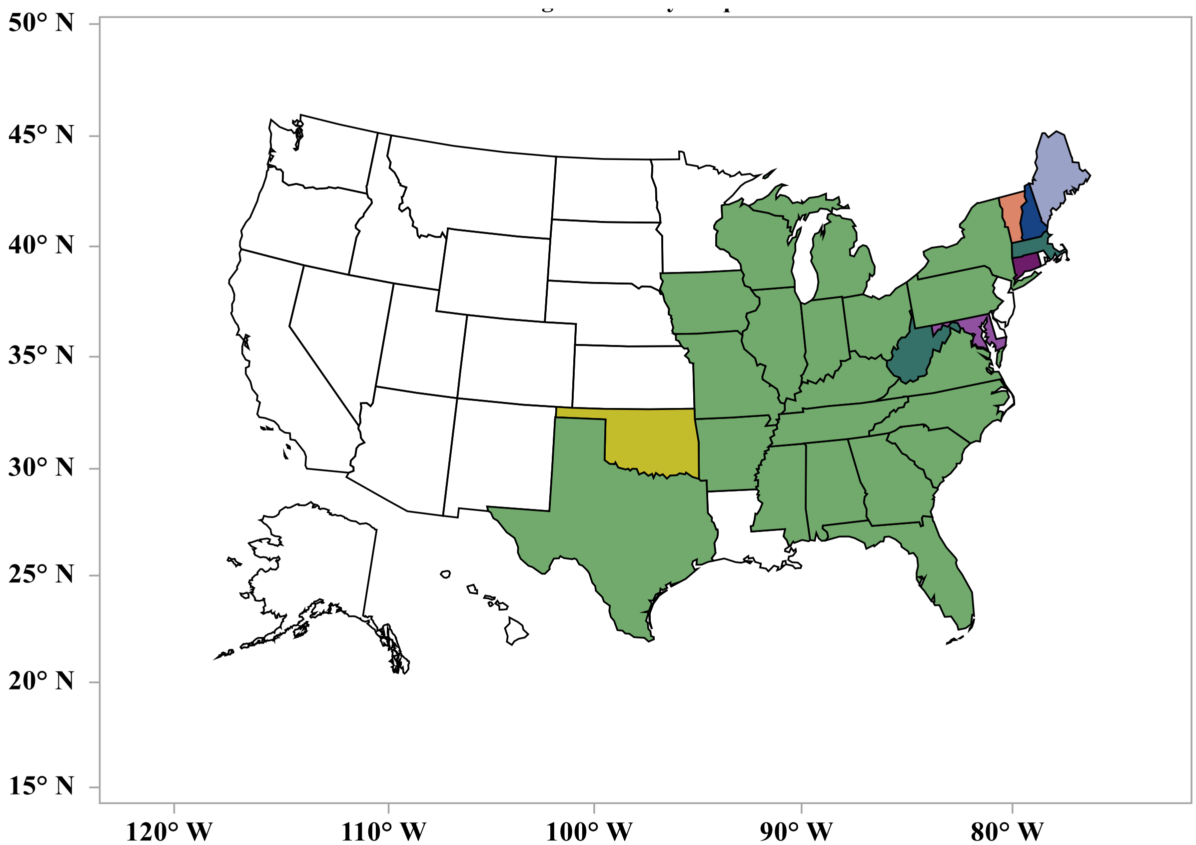

Figure 4-1: States surveyed for this research.

The study population could be all hardwood lumber producers in the US. According to Howard et al. (2016) US lumber production report, most hardwood mills, over 98%, were in the south, east, and northern regions of the US. Thus, the survey was limited to hardwood lumber producers from these regions only. A total of 2040 sawmills were identified as hardwood processing sawmills, which is the total number of samples for this survey.

4.1.3 Defining the Purpose of the Questionnaire

This questionnaire was designed to measure the current ability of hardwood sawmills to produce SGHL.

4.1.4 Questionnaire Design for the Survey

The questionnaires for this survey were designed under the framework described by Groves et al. (2009) and approved by the Internal Review Bureau (IRB) of Virginia Tech. Groves et al. (2009) compared questionnaire design in survey research as new product design strategies. Questionnaires are a simple research method used to gather information from many respondents quickly. However, the questionnaires' design is challenging and requires a lot of skill and consideration (Wilson 2013). Four steps defined by Groves et al. (2009) to design questionnaires are:

1. Determine and define the purpose of the questionnaire.
2. Finalize the sampling requirement.
3. Develop a strategy to build trust with respondents to gain the best response rate.
4. Design the questionnaire in straightforward and unequivocal sentences, based on a data analysis plan.

Questions were designed following all four steps for questionnaires designed by Groves et al. (2009) to measure the current capability of sawmills based on existing technology, awareness of sawmills, grading capability, production strategies of the sawmills, along with requirements of various resources and possible collaboration with other sawmills or CLT manufacturers. The requirements of various resources by the sawmills to implement production strategies to produce SGHL define the sawmills' current ability.

4.1.5 Strategies to Gain a Higher Response Rate

The questionnaire's design and implementation met the Tailored Design Method (TDM) requirements to obtain the best response rate. According to the TDM, the response rate increases when participants feel that the cost of participation is low, the reward is high, and the source is trustworthy (Dillman et al. 2009). The following tools were used in the questionnaire design to increase the response rate:

To lower the cost -

- All relevant questions were drafted, and a brief introduction was presented before questions when necessary.
- Short and easy to complete questionnaires were drafted, and sawmills needed minimum input to participate.
- Questionnaires were drafted to be used in both online and mail format. The sawmill had the choice of which to use.

To increase the reward -

- All questionnaires were drafted to be respectful to sawmills.
- Sawmills were requested for help as participants.
- Sawmills were thanked for their help and support.
- Sawmills were made aware of the usefulness of this research to expand the hardwood lumber market.

To build trust -

- Sawmills were informed that the funding for this survey had been received from legitimate authorities.
- A request to participate and a "thank-you" letter were drafted to all sawmills to show appreciation for their help in advance.
- Sawmills were assured that the information collected was secure and confidential.
- Sawmills had the usage of the collected data explained to them.

- The research team contact information was provided to all sawmills.

4.1.6 Questions Included in the Questionnaire

The questionnaire had three sections; the first section collected the sawmills' demographics, such as species sawn at the sawmills, annual production volume, percentage of lower grade lumber using current sawing practices, and average production cost. The second section was designed to collect information on current capacity and practices of the sawmills, awareness of structural grading of hardwood, expected demands for new products, estimated lumber value for the SGHL, production strategies of the sawmills, current technology, supply chain practices, market and marketing issues, collaboration opportunities and investment opportunities. The third section focused on the need for technology and resources for the sawmills to produce SGHL. The answers to the third section were dependent on the responses from the other two sections since it measured the additional need for resources for the sawmills to begin the production of SGHL. The final draft of the questionnaire is attached in Appendix B.

4.1.7 Survey Trial, Dispatch, and Response Recording

A list of sawmills was obtained from the " Forest Products Network" database and the database service company "SicCode." Both databases were merged, and all duplicates were removed to obtain a final list of the sawmills. A total of 2040 sawmills were identified as hardwood processing sawmills, the total number of the samples for this survey. This survey was delivered by two methods, paper and the internet. A paper survey was sent to all 2040 sawmills. An internet survey was designed and delivered through Qualtrics to all sawmills with the email contact available in the database. Only 485 sawmills had an email contact. A trial survey was conducted through Qualtrics with 15 sawmills from the US's southeastern region to test the questionnaires. The questionnaires were edited to address the suggestions from some of the sawmills. Final questionnaires were prepared in both paper and Qualtrics format.

Both the paper and Qualtrics surveys were distributed on the same date. Both methods clearly explained the opportunity to use both data collection methods and asked participants to choose only one method. For the mixed mode of data collection, response collection should be observed for the bias based on the delivery mode. In this case, a paper survey and Qualtrics is a visual mode of data collection, so it produced a similar response, and the response can be used to analyze data as an unimode data collection method (de Leeuw et al., 2018). During design, each question should be designed similarly in both modes, and responses should be tallied to remove duplicates if they exist (Dillman et al., 2009). A standard method should be selected to drop either mode of response to remove duplicates (de Leeuw et al., 2018).

The second wave of surveys was sent 35 days after the first survey was sent to 1941 companies, eliminating the companies' names that had responded from the first wave. The second wave of internet surveys was also sent on the same date as the hard copies. A final reminder was sent to all sawmills 30 days after the second wave of distribution and requested that they complete the survey soon. The online survey was closed 95 days after the first distribution of the survey.

4.1.8 Data Recording, Data Preparation, and Data Analysis Method

Each response from the paper survey was recorded in an Excel sheet specially designed to record each question's response. All the survey responses were individually recorded. Each sawmill was assigned a number based on the receiving date to identify and verify the sawmill. The response obtained from the internet survey was stored in a Qualtrics database until the survey was closed. The final survey responses from Qualtrics were downloaded in Excel format and merged with the paper survey responses. Both sources were marked and recorded for further analysis.

Before analyzing the responses, each question was coded based on the response from the sawmills. Two different datasheets were prepared to analyze the survey responses. The first datasheet included the actual responses from the sawmills used for the categorical analysis of the data. The second sheet was a model to obtain the participating sawmills' readiness (current ability) index (RI) to observe the relationship between categorical variables with RI.

The responses from the survey were primarily collected in nominal scales. Each question from section one had a categorical response other than the tree species sawn at the sawmill. The responses from the second section of the survey were recorded as nominal data that excluded two questions. The question for minimum annual demand and production strategies of the sawmills that is based upon the minimum lumber value of the SGHL was designed to obtain a categorical response. These questions were designed to convert the categorical responses into a nominal scale for the analysis. Each question from the third section of the questionnaires was designed on a nominal scale. All the demographic variables were modeled to identify the sawmill type, sawmill size, percentage of lower grade lumber, and the average production cost per 1000 bf of hardwood lumber.

The RI was calculated based on the sawmills' responses to the third section of the questionnaire. If sawmills needed all resources listed in the section, then the RI of the sawmill was determined as zero. If a sawmill responded that it did not need any additional resources to begin producing SGHL, its RI value was six. There were six various resources listed to measure the sawmills' current requirements to evaluate RI, and one resource carried 1 point. If the respondent indicated the resource as a need, that reduced the RI by one point for each resource type. Many sawmills had the basic idea of sawmill requirements, so the RI in this study was evaluated on a nominal scale.

4.2 Observation and Results

4.2.1 Reliability and Validity of the Survey

The survey was sent to 2040 sawmills in the first wave from the Midwest, southern, northern, and eastern regions of the US. From the survey database pool, 485 sawmills were contacted through two different means of data collection, paper and an internet survey. Approximately 19% of the paper surveys were returned with some type of response. However, only 22% of the returned responses were complete enough to be used for further analysis, accounting for 4% of the total surveys sent to sawmills. From the Qualtrics survey, out of 485 surveys, only 24% of the sawmills responded. Only 42 surveys were completed and used for the data analysis purpose. The combined response of the survey was 124, which was approximately 6% of the data pool. As the adjusted sample pool was 1938, after removing all non-delivered mail, the response rate of useful data increased to 6.4%. Details of the survey are explained in Table 4-1.

Table 4-1: Information on survey sample pool and sawmill responses

Particular	Counts	Particular	Counts
Total survey sent by mail	2040	Total survey sent by Qualtrics	**485**
Total returned by mail	384	Total response from Qualtrics	**118**
Total completed responses from mail	82	Total returned as nondelivered from Qualtrics	**93**
Total returned as nondelivered	103	Total completed response from Qualtrics	**42**
Total useful responses	124		
Useful response percentage		**6.1%**	

The demographics of the surveys distributed by the state are presented in Figure 4-2.

4.2.1.1 Nonresponse Bias test

The nonresponse bias is defined as the difference between the answers of non-respondents and the respondents of the survey (Lambert et al. 1990). A nonresponse bias test is necessary to generalize the survey's observed results as a data collection instrument. This study assumed a difference between an early respondent and the late respondent of the survey (Lahaut et al. 2003 & Espinoza et al., 2011). All the respondents were classified into two groups corresponding to the time of the response. The response obtained from the first distribution of the mail survey was categorized as "Wave 1." The response was obtained after distributing the second set of surveys, and a reminder postcard was recorded as "Wave 2."

Sawmill production capacity was referenced to analyze the non-response bias test. The contingency plot of the sawmill's capacity vs. the waves had a p-value of 0.1320. Thus, it can be assumed that the participating sawmills' overall demographics are from the same sample pool. However, it is necessary to caution against the observed results' generalization because the survey response rate was only 6.4%.

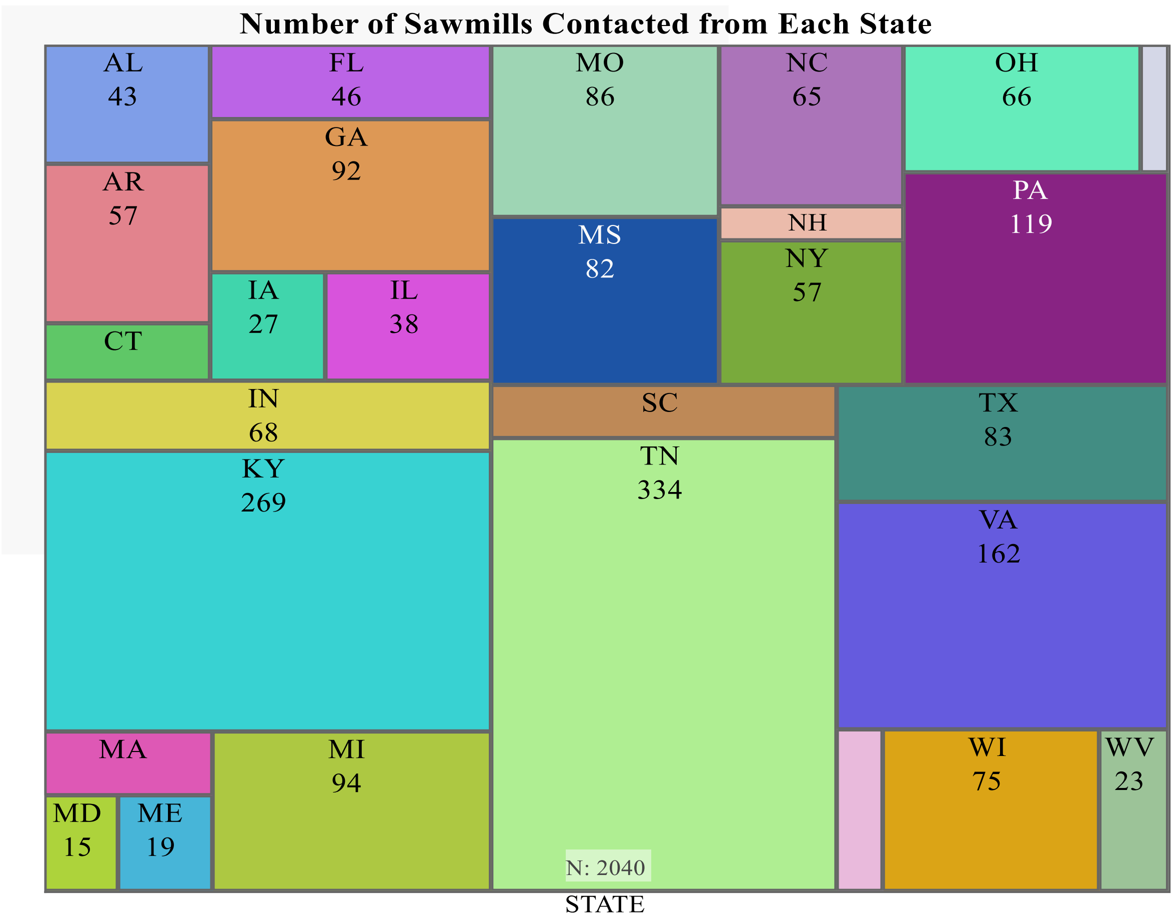

Figure 4-2: Number of surveys distributed by the state.

4.2.2 Measuring the Validity of the Questionnaires

Other than a demographic question, the questionnaires were designed to measure the current capability of the sawmills. For survey data, each question has a unique answer. However, a group of questions that aim to collect responses should measure the same variables (Zinbarg et al., 2005). Each of these questions, or groups of questions, must have a unique relation to the final response; otherwise, the questions' response does not measure the same response. Thus, it is vital to validate the questionnaires. One method to test the survey's validity was to observe Cronbach's α (Zinbarg et al. 2005). Cronbach's α is a reliability test measure applied to measure the questionnaire analysis (Cronbach 1951). It is defined as:

$$\alpha = \frac{k * c}{(v + (k-1) * c}$$

where:

k = the number of items in the scale

c = the average covariance between items

v = the average variance between items

Questions regarding the sawmill's demographics, the sawmill's current capacity, planned production strategies, and necessary resources to produce SGHL in the questionnaires had Cronbach's α higher than 0.7. Thus, the data collection instrument for this research was a valid and reliable tool.

The responses collected from the survey are presented in two sections. The first section includes information on the demographics of the participating sawmills. The second section includes analyzing the responses based on the sawmills' resources to produce SGHL.

4.2.3 Demographics of the Participating Sawmills

Out of 124 sawmills, 121 sawmills responded with the percentage of hardwood lumber produced in 2018 by species. The major species sawn was red oak, which accounted for approximately 30% on average, ranging from zero to 80% of the total lumber volume for one sawmill. The second and third species sawn in a participating sawmill were yellow poplar and white oak, which had a mean of around 15% for both. There was one sawmill that produced only yellow poplar lumber together with softwood lumber. The maximum volume of the white oaks sawn was approximately 69%. The sawmills producing a higher volume of white oaks also had higher production costs than other sawmills. Hard maple and soft maples were the other dominant hardwood species sawn in the participating sawmills, accounting for an average of 9% and 8% by volume of the total lumber produced. The details of the various species are presented in Figure 4-3.

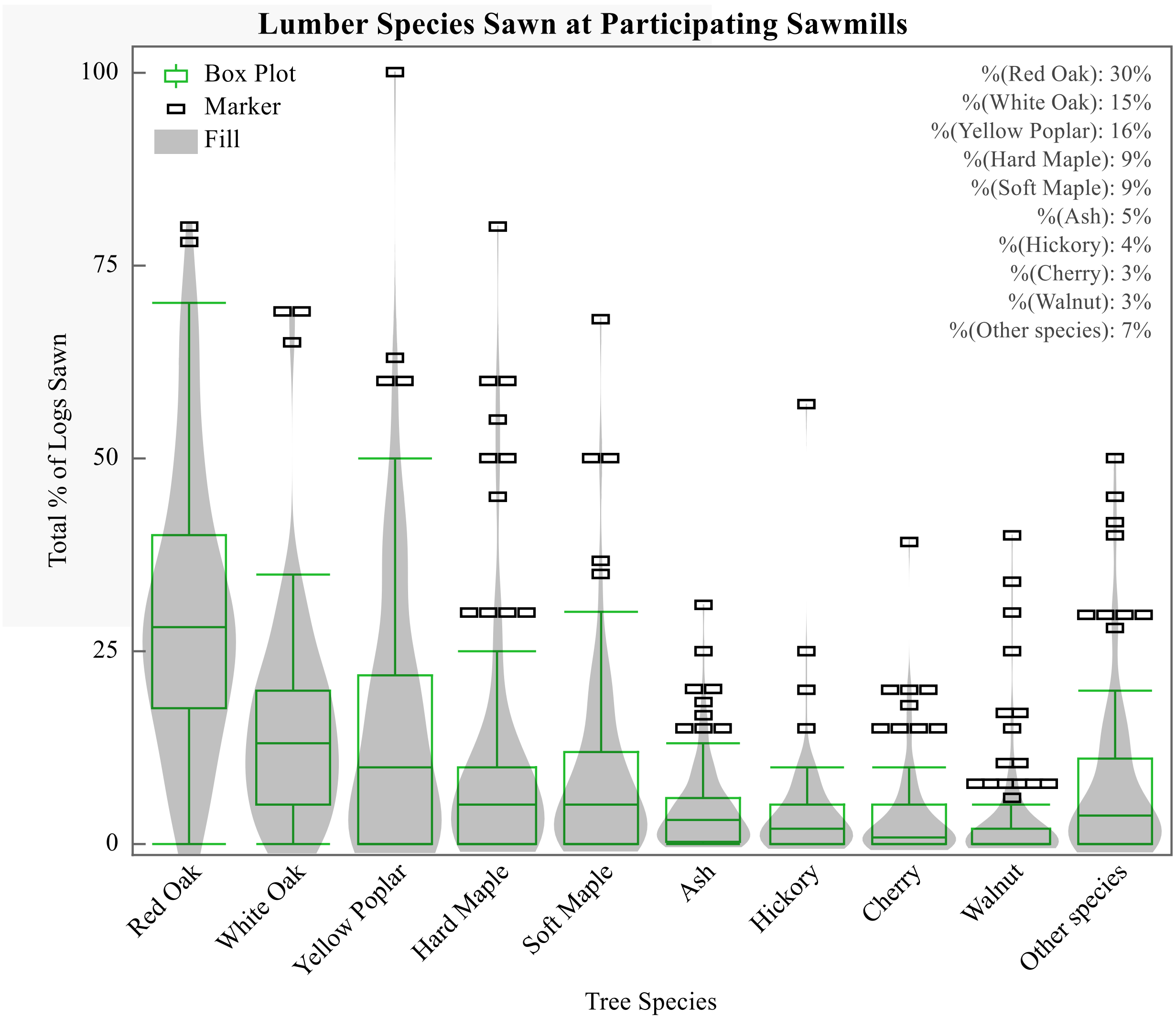

Figure 4-3: Lumber production volume of sawmills by species.

Most of the participating sawmills, approximately 56%, had an annual production capacity of less than 10 million bf of lumber. Only about 5% of the participating sawmills had an annual production capacity higher than 35 million bf. Twenty-six percent of the sawmills had a production capacity of between 10 million bf and 20 million bf. In contrast, about 12% of the sawmills had production capacity between 20 million bf and 35 million bf. Approximately 70% of the participating sawmills produced only hardwood lumber, and the remaining 30% produced both hardwood and softwood lumber. More than 63% of the sawmills that produced both hardwood and softwood lumber were producing at least 50% hardwood lumber by volume. The distribution of lower grade lumber and production cost is presented in Figure 4-4:

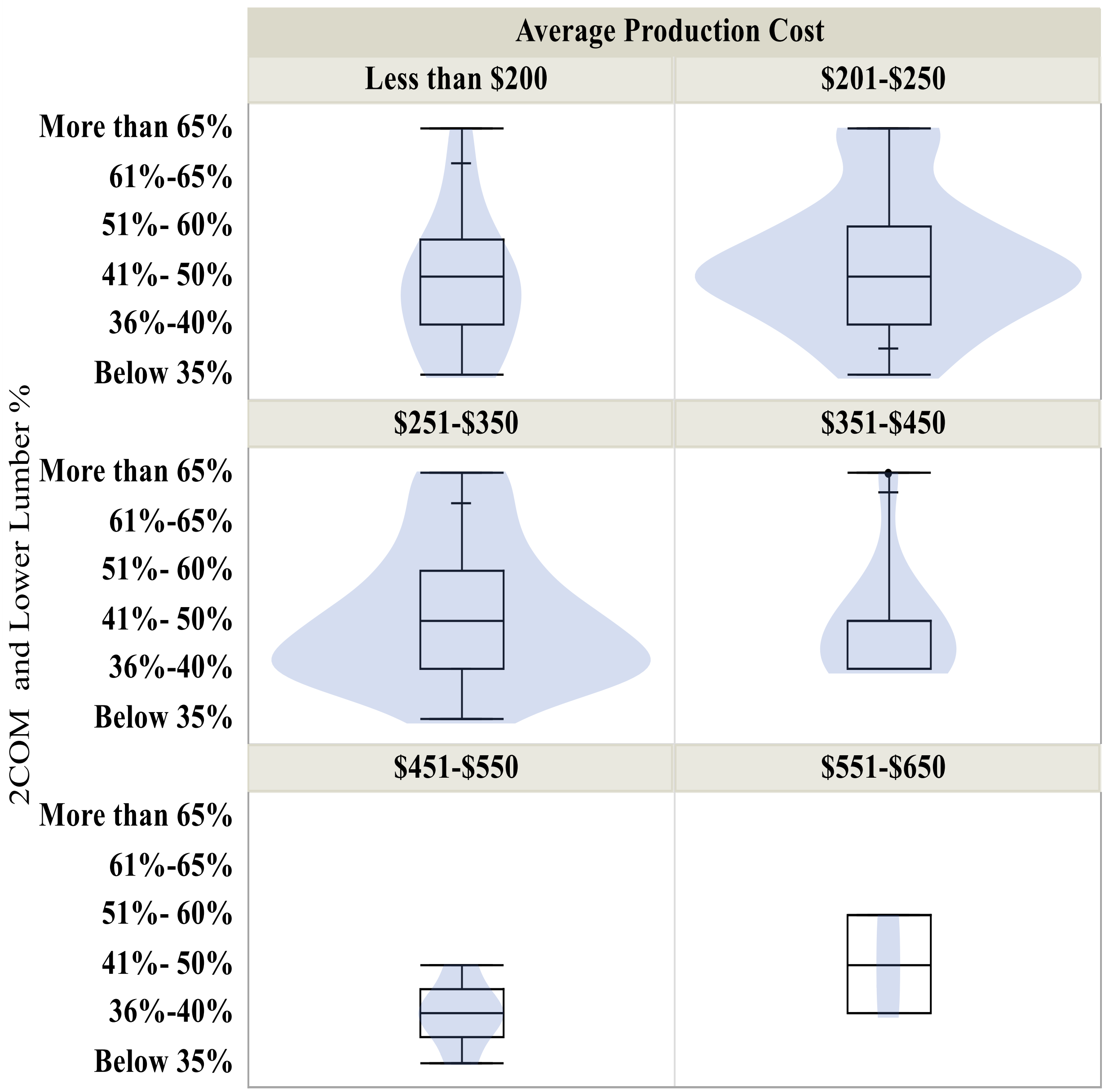

Figure 4-4: Volume of 2 com and lower grade lumber by the average production cost

Lumber of 2 common and lower grade grades for most of the sawmills was between 40% and 60% of the total lumber produced. The percentage of lower grade lumber varied greatly depending upon the species and grade of the logs sawn at the sawmill. Sawmills that saw higher grade logs had a lower percentage of 2 common and lower grade lumber and vice-versa. More than 84% of the sawmills had production costs below $350 per 1000 bf of lumber. Around 49% of the sawmills had production costs less than $250 per 1000 bf of lumber. It was not clear from the survey results what grade of the log was being sawn at the sawmills, so it was not easy to generalize the results. Though from the observed data, sawmills producing a higher percentage of the lower grade lumber also reported lower production costs.

The participating sawmills had a wide range of production costs based on their production technology and the species they chose to process. The observed production cost of the sawmills by various lumber sawn species is presented in Figure 4-5. The detailed demographics of the sawmills based on sawn species, production capacity, hardwood lumber production volume, the lower grade lumber volume, and production cost are summarized in Table 4-2.

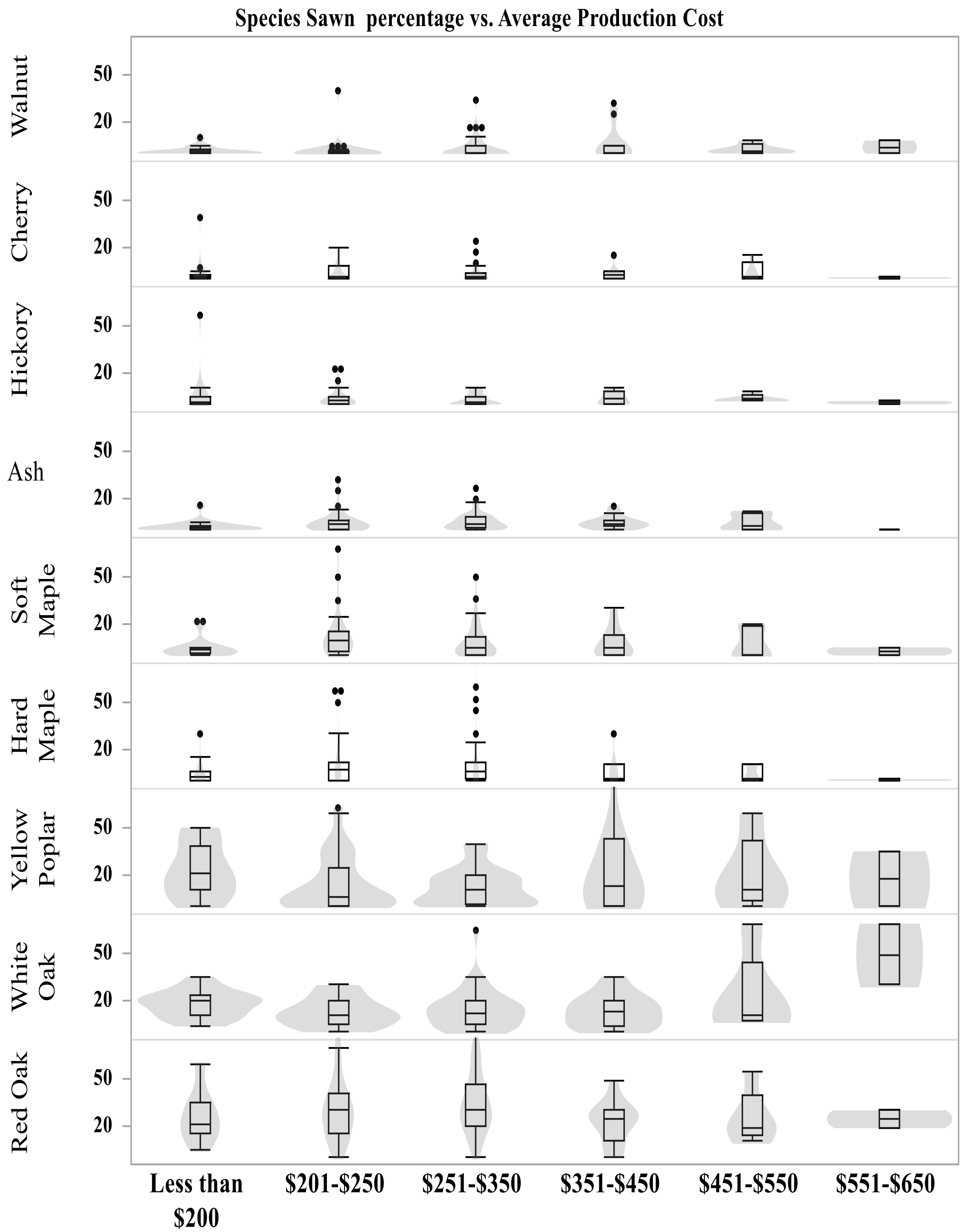

Figure 4-5: Production cost distribution by species sawn

Table 4-2: Demographic summary of the participating sawmills by hardwood species sawn.

Particular	N	Red Oak	White Oak	Yellow Poplar	Hard Maple	Soft Maple	Ash	Hickory	Cherry	Walnut	Other species
Production Capacity											
Below 10 MMBF	70	29.32	13.59	13.25	9.82	10.90	4.61	4.21	3.20	3.05	8.34
10 to 15 MMBF	25	29.80	15.34	17.93	11.33	5.80	4.77	3.63	3.16	1.42	6.88
16 to 20 MMBF	8	23.00	28.50	22.88	8.25	4.25	3.13	2.13	0.50	4.75	2.63
21 to 25 MMBF	6	39.82	16.54	13.72	3.19	2.74	3.15	4.68	1.54	4.49	10.14
26 to 30 MMBF	6	24.67	11.17	18.75	9.67	13.50	6.25	2.83	8.83	2.33	2.00
31 to 35 MMBF	3	33.00	22.33	32.00	3.00	1.33	2.00	0.67	1.33	2.00	2.33
More than 35 MMBF	6	41.47	9.82	12.69	7.27	5.89	5.78	1.00	8.08	0.00	8.01
Total	124	29.88	15.01	15.55	9.40	8.73	4.54	3.69	3.37	2.73	7.27
HW Production Volume %											
0%-10%	2	15.50	14.00	8.50	2.00	15.00	1.00	28.50	1.00	4.50	10.00
11%-20%	3	80.00	10.00	0.00	0.00	0.00	5.00	2.00	0.00	0.00	3.00
21%-30%	3	46.67	16.67	15.67	3.33	3.33	3.33	3.33	1.67	0.33	5.67
31%-40%	3	45.33	15.00	20.67	0.00	1.67	4.00	1.67	0.00	0.00	11.67
41%-50%	3	26.67	8.33	38.33	1.00	1.67	0.33	8.33	0.00	1.67	20.50
51%-60%	4	54.75	22.25	12.25	0.00	3.00	1.38	0.88	2.75	1.25	1.50
61%-70%	7	28.00	18.86	22.29	10.57	4.43	4.14	0.29	0.86	0.33	10.29
71%-80%	6	27.00	17.80	20.40	6.40	4.00	1.60	4.20	3.60	9.40	5.60
81%-90%	7	35.14	13.57	23.86	2.29	4.71	3.57	2.86	0.57	1.00	12.43
91%-100%	85	27.03	14.39	13.61	11.75	10.71	5.25	3.54	4.25	2.97	6.61
Total	123	29.67	14.89	15.60	9.48	8.80	4.53	3.72	3.40	2.76	7.33
2 common and Lower Lumber %											
Below 35%	11	26.46	17.82	22.65	4.96	4.76	2.29	5.75	3.85	1.72	9.74
36%-40%	38	29.83	12.60	13.82	10.62	11.53	4.94	3.79	4.34	1.54	7.40
41%-50%	39	33.42	14.02	12.17	11.71	8.36	5.11	2.94	2.53	3.34	6.47
51%-60%	18	22.64	13.27	22.82	6.18	8.00	4.73	3.73	2.91	5.91	9.82
61%-65%	7	25.40	22.60	20.40	4.40	7.60	5.00	3.60	4.20	2.60	4.20
More than 65%	11	24.50	49.50	17.50	0.50	2.50	0.00	1.00	0.50	4.00	0.00
Total	124	29.80	14.92	15.54	9.44	8.80	4.55	3.67	3.40	2.73	7.33
Average Production Cost											
Less than $200	16	23.91	11.09	18.91	10.55	8.00	1.64	7.82	2.09	1.55	14.45
$201-$250	44	24.98	16.46	13.08	11.88	8.80	6.15	3.81	4.33	3.89	6.61
$251-$350	45	31.89	15.35	16.06	9.87	8.33	3.87	2.21	3.36	3.28	5.94
$351-$450	11	31.84	14.23	24.13	5.66	7.29	4.47	2.56	3.21	2.09	4.78
$451-$550	5	50.83	17.83	4.50	3.67	4.17	3.67	4.75	0.25	0.20	10.17
$551-$650	2	30.73	12.64	10.73	7.55	15.45	4.91	5.55	3.36	0.10	9.00
Total	123	29.88	15.01	15.55	9.40	8.73	4.54	3.69	3.37	2.73	7.27

4.2.4 **Status of the Sawmills**

Sawmills had adopted a wide range of technology and sawing practices in response to their market. The discrepancy in the adopted technologies is an important limiting factor for beginning to produce SGHL. Sawmills' responses were collected to measure the capacity to saw standard SGHL as a product mix in regular sawing procedures. Also, sawmill's responses were collected about producing SGHL from hardwood cants and their current capacity to surface four sides of the lumber and kiln dry the lumber to produce SGHL. Almost 90% of the sawmills could saw SGHL as a product mix, and more than 97% could process hardwood cants. Less than 24% of the sawmills could surface all four sides of the lumber. Fifty percent of the sawmills had adequate kiln capacity, and 27% of the sawmills also had excess kiln capacity. Most of the sawmills with excess kiln capacity had 10-30% excess capacity. The distribution of the sawmill capacity for various demographic measures is presented in Table 4-3.

Structural grading of hardwood lumber is not a common practice in hardwood industries. However, very few sawmills produced SGHL due to consumer demand from yellow poplar (Green, 2005). Sawmills were asked for their awareness of SGHL, grading rules for SGHL, and the currently employed graders' capabilities to grade SGHL. The survey respondents indicated that more than 86% of the sawmills were aware of SGHL. Only 51% were aware of the grading rules. The results also indicate that more than 60% of graders currently working in participating sawmills could not grade hardwood lumber for structural application. The summarized responses of the sawmills are presented in Table 4-4.

The expected demand for CLT in the US will require about 200 million bf of lumber by 2020 (The Beck Group, 2018). For CLT manufacturing facilities' efficient and economical operation, it is vital to establish a sustainable supply of quality raw material. A sustainable supply chain requires the right value from the product to the producer. Sawmills were asked the minimum value of SGHL produced in their sawmills that would encourage them to begin commercial production of the SGHL. Twenty-seven percent of the sawmills responded that the minimum value of SGHL would need to be 5% to 10% higher than NHLA grade lumber.

Additionally, the other 25% of the sawmills were ready to produce SGHL on a commercial scale for a value equal to NHLA grade lumber.

The demand for the product is the primary factor in attracting sawmills to produce a new product. For sawmills to produce SGHL, the market needs to show significant demand. Sawmills were asked to indicate the minimum SGHL demand to begin producing it on a commercial scale. Most of the sawmills, around 48%, indicated that the annual demands of SGHL should be higher than 5 million bf for them to begin the production on a larger scale. The response for the required minimum annual demand and lumber value of SGHL is summarized in Table 4-5.

Structural graded hardwood lumber would be a new product for hardwood sawmills. For the commercial production of new products, sawmills must include changes to their existing production strategies. The production department must incorporate the required changes to produce SGHL as a product mix. If a sawmill chose to begin producing a new product, its potential revenue would determine the production strategies. Each sawmill was asked about their production strategies for different values of SGHL. If SGHL value were up to 5% more than NHLA grade lumber value, 26% of the participating sawmills would produce only NHLA grade lumber. Twenty-five percent of the sawmills would choose to produce only mix-grade lumber, and 17% would choose to produce either of them that yield higher revenue, based on the market at that time. The distribution of the response is summarized in Table 4-6. For more than 5% higher value of SGHL, only 10% of the sawmills would choose to produce only NHLA grade lumber, and others would choose to produce mixed grade lumber. The distribution of the responses from each sawmill is summarized in Table 4-7.

As the demand for CLT increases, the demand for lumber also increases significantly. The current production capacity of the US meets 65% of the total demand for SGHL. When CLT manufacturers choose to use structural hardwood lumber, then hardwood sawmills will see significant demand for SGHL. Producing SGHL as a product mix only converts some portion of the lower grade lumber into SGHL, but not all lower-grade lumber can be converted into SGHL. So, the SGHL lumber volume would be limited for many sawmills and may not produce and meet 100% of CLT mills' demand by themselves. Thus, to begin SGHL production, match the SGHL demand, distribute SGHL, and upgrade the current technology of sawmills, sawmills may need to collaborate on various aspects. Sawmills were asked to indicate their willingness to collaborate with other stakeholders, based on their need to meet production requirements and match the projected SGHL demands.

Approximately 78% of hardwood sawmills responded positively toward collaborating with other sawmills to meet CLT manufacturers' annual demand. Over 58% of the sawmills were willing to share a grader with other sawmills to grade SGHL. Seventy-five percent of the sawmills responded positively to sharing production information with CLT manufacturing companies to improve product quality. More than 80% of the sawmills were opened to collaborating with brokers and lumber suppliers to expand the SGHL market. Seventy-one percent of the sawmills responded positively to sharing investments with CLT industries to meet quality lumber demand. Details of the responses are summarized in Table 4-8.

With some exceptions, hardwood sawmills need to find additional resources to produce SGHL. Each of the sawmills was asked to indicate the additional resources required to begin the commercial production of SGHL. About 40% of the sawmills indicated the need for sawing technology and equipment. More than 70% indicated the need for a certified SGHL grader. Over 56% of the sawmills required additional sorting capacity, and 60% of the participating sawmills needed additional kiln capacity. More than 78% of the sawmills indicated an additional four side planer and about 56% of the sawmills needed to find an additional lumber storage facility. The response by various demographic measures is presented in Table 4-9.

Table 4-3: Distribution of the sawmill's capacity by various demographic measures.

Particular		SGHL Sawing Capacity		Can saw cants for SGHL		S4S Capacity		Have enough kiln Capacity		Have Excess Kiln Capacity	
	N	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Production Capacity											
Below 10 MMBF	70	6	63	1	68	55	13	49	19	57	11
10 to 15 MMBF	25	2	23	1	24	17	8	7	18	15	10
16 to 20 MMBF	8	3	5	1	7	6	2	0	8	5	3
21 to 25 MMBF	6	0	6	0	6	6	0	2	4	3	3
26 to 30 MMBF	6	0	6	0	6	3	3	1	5	3	3
31 to 35 MMBF	3	0	3	0	3	3	0	3	1	2	1
More than 35 MMBF	6	2	4	0	6	3	3	0	6	4	2
Total	124	13	110	3	120	93	29	61	61	89	33
HW Production Volume %											
0%-10%	2	0	2	0	2	2	0	1	1	2	0
11%-20%	3	0	3	0	3	2	1	1	2	2	1
21%-30%	3	0	3	0	3	3	0	1	2	3	0
31%-40%	3	1	2	0	3	1	2	0	3	2	1
41%-50%	3	0	3	0	3	2	1	1	2	0	3
51%-60%	4	1	3	0	4	4	0	1	3	3	1
61%-70%	7	0	7	0	7	5	1	5	1	5	1
71%-80%	6	0	6	0	6	3	3	1	5	3	3
81%-90%	7	1	6	1	6	5	2	3	4	5	2
91%-100%	85	10	74	2	82	65	19	47	37	63	21
Total	123	13	109	3	119	92	29	61	60	88	33
2 common and Lower Lumber %											
Below 35%	11	0	11	0	11	8	2	7	3	10	0
36%-40%	38	7	31	1	37	29	9	15	23	27	11
41%-50%	39	4	35	1	38	30	9	16	23	27	12
51%-60%	18	0	18	1	17	14	4	9	9	11	7
61%-65%	7	1	6	0	7	6	1	4	3	5	2
More than 65%	11	1	9	0	10	6	4	10	0	9	1
Total	124	13	110	3	120	93	29	61	61	89	33
Average Production Cost											
Less than $200	16	1	15	1	15	14	2	13	3	15	1
$201-$250	44	3	41	0	44	33	10	24	19	28	15
$251-$350	45	5	39	0	44	33	11	19	25	33	11
$351-$450	11	1	10	0	11	7	4	5	6	8	3
$451-$550	5	1	4	0	5	3	2	0	5	3	2
$551-$650	2	1	1	1	1	2	0	0	2	2	0
Total	123	12	110	2	120	92	29	61	60	89	32

Table 4-4: Distribution of the sawmill's awareness and capacity by various demographic measures.

Particular		Aware of SGHL		Aware of SGHL grading rule		Graders can grade SGHL.	
	N	No	Yes	No	Yes	No	Yes
Production Capacity							
Below 10 MMBF	70	10	59	31	38	44	25
10 to 15 MMBF	25	4	21	17	8	13	12
16 to 20 MMBF	8	0	8	1	7	5	3
21 to 25 MMBF	6	1	5	4	2	6	0
26 to 30 MMBF	6	1	5	2	4	1	5
31 to 35 MMBF	3	0	3	1	2	2	1
More than 35 MMBF	6	1	5	4	2	5	1
All	124	17	106	60	63	76	47
HW Production Volume %							
0%-10%	2	1	1	1	1	2	0
11%-20%	3	0	3	1	2	1	2
21%-30%	3	0	3	1	2	1	2
31%-40%	3	1	2	2	1	2	1
41%-50%	3	0	3	1	2	2	1
51%-60%	4	2	2	4	0	3	1
61%-70%	7	0	7	4	3	4	3
71%-80%	6	0	6	0	6	4	2
81%-90%	7	1	6	3	4	3	4
91%-100%	85	12	72	43	41	53	31
All	123	17	105	60	62	75	47
Average Production Cost							
Less than $200	16	3	13	9	7	13	3
$201-$250	44	8	36	22	22	25	19
$251-$350	45	3	41	22	22	30	14
$351-$450	11	3	8	5	6	5	6
$451-$550	5	0	5	1	4	2	3
$551-$650	2	0	2	0	2	1	1
All	123	17	105	59	63	76	46
2 common and Lower Lumber %							
Below 35%	11	2	9	6	5	7	4
36%-40%	38	5	33	19	19	23	15
41%-50%	39	4	35	17	22	22	17
51%-60%	18	2	16	8	10	10	8
61%-65%	7	1	6	4	3	5	2
More than 65%	11	3	7	6	4	9	1
All	124	17	106	60	63	76	47

Table 4-5: Required minimum annual demand and lumber value to produce SGHL

Particular	N	Required minimum annual demand				The minimum lumber value compares to NHLA.			
		Up to 1	Up to3	Up to5	More than 5	Equal	1- 5%	5-10%	> 10%
Production Capacity									
Below 10 MMBF	70	2	18	7	35	11	13	17	24
10 to 15 MMBF	25	0	10	8	7	9	1	8	7
16 to 20 MMBF	8	0	2	4	1	2	1	2	2
21 to 25 MMBF	6	0	1	1	3	1	0	2	2
26 to 30 MMBF	6	2	1	1	2	3	1	2	0
31 to 35 MMBF	3	0	0	2	1	1	0	1	0
More than 35 MMBF	6	0	0	0	4	1	2	0	3
All	124	4	32	23	53	29	18	32	38
HW Production Volume %									
0%-10%	2	0	1	0	0	0	0	0	1
11%-20%	3	0	1	0	1	1	0	0	1
21%-30%	3	0	1	1	1	1	0	2	0
31%-40%	3	0	0	0	3	1	1	0	1
41%-50%	3	0	1	2	0	0	1	2	0
51%-60%	4	0	1	1	1	0	0	1	2
61%-70%	7	0	1	2	2	1	1	4	1
71%-80%	6	0	0	2	3	0	3	2	1
81%-90%	7	1	2	1	3	3	0	2	2
91%-100%	85	3	24	13	39	22	12	19	28
All	123	4	32	22	53	29	18	32	37
Average Production Cost									
Less than $200	16	0	1	0	11	3	2	7	2
$201-$250	44	0	12	7	20	8	9	12	13
$251-$350	45	2	12	12	17	14	5	9	15
$351-$450	11	1	4	2	3	2	2	2	4
$451-$550	5	1	3	0	1	1	0	1	3
$551-$650	2	0	0	1	1	0	0	1	1
All	123	4	32	22	53	28	18	32	38
2 common and Lower Lumber %									
Below 35%	11	0	5	0	3	0	3	2	4
36%-40%	38	3	12	6	14	11	4	8	15
41%-50%	39	0	8	7	21	10	5	12	10
51%-60%	18	1	5	6	6	5	2	5	6
61%-65%	7	0	1	3	2	2	1	4	0
More than 65%	11	0	1	1	7	1	3	1	3
All	124	4	32	23	53	29	18	32	38

Table 4-6: Sawmill's production strategies for SGHL value equal and less than 5% higher than NHLA grade lumber

Particular	N	ALL	CANTs only	Mix Grade	Mix Grade only	NHLA Only	NHLA+ CANTs	Dimensional Only	Dimensional + CANTs
Production Capacity									
Below 10 MMBF	70	16	2	4	18	9	2	1	13
10 to 15 MMBF	25	4	2	0	10	0	1	2	5
16 to 20 MMBF	8	2	1	1	1	1	0	1	0
21 to 25 MMBF	6	3	0	0	1	1	0	0	0
26 to 30 MMBF	6	4	0	0	1	0	0	0	1
31 to 35 MMBF	3	0	0	0	1	0	0	0	1
More than 35 MMBF	6	3	0	0	1	1	0	0	0
All	124	33	5	5	33	12	3	4	20
HW Production Volume %									
0%-10%	2	0	0	0	1	0	0	0	0
11%-20%	3	0	0	0	1	0	1	0	0
21%-30%	3	3	0	0	0	0	0	0	0
31%-40%	3	2	0	0	1	0	0	0	0
41%-50%	3	0	0	1	1	0	0	0	1
51%-60%	4	2	0	0	1	0	0	0	0
61%-70%	7	2	1	0	1	1	0	0	2
71%-80%	6	0	0	0	3	1	0	0	1
81%-90%	7	1	0	0	2	2	0	1	1
91%-100%	85	23	4	4	21	8	2	3	15
All	123	33	5	5	32	12	3	4	20
Average Production Cost									
Less than $200	16	5	1	1	3	1	0	1	2
$201-$250	44	8	2	3	13	3	2	0	9
$251-$350	45	16	2	0	12	6	0	1	6
$351-$450	11	2	0	1	3	1	1	0	2
$451-$550	5	1	0	0	1	0	0	2	1
$551-$650	2	1	0	0	0	1	0	0	0
All	123	33	5	5	32	12	3	4	20
2 common and Lower Lumber %									
Below 35%	11	2	1	0	3	1	0	0	2
36%-40%	38	12	2	0	10	3	1	3	6
41%-50%	39	13	0	2	14	3	1	0	4
51%-60%	18	5	1	1	5	1	1	0	3
61%-65%	7	0	0	0	1	0	0	1	4
More than 65%	11	1	1	2	0	4	0	0	1
All	124	33	5	5	33	12	3	4	20

Table 4-7: Sawmill's production strategies for SGHL value is more than 5% higher than NHLA grade lumber

	N	ALL	CANTS Only	Mix Grade	Mix Grade Only	NHLA Only	NHLA + CANTS	Dimensional Only	Dimensional + CANTS
Production Capacity									
Below 10 MMBF	70	9	4	0	12	20	1	2	14
10 to 15 MMBF	25	4	3	1	9	3	1	3	0
16 to 20 MMBF	8	2	0	1	2	2	0	0	0
21 to 25 MMBF	6	0	0	0	2	2	0	0	0
26 to 30 MMBF	6	2	0	1	1	0	0	0	2
31 to 35 MMBF	3	1	0	1	1	0	0	0	0
More than 35 MMBF	6	1	0	0	1	2	1	0	0
All	124	19	7	4	28	29	3	5	16
HW Production Volume %									
0%-10%	2	0	1	0	0	0	0	0	0
11%-20%	3	0	1	0	0	0	0	0	1
21%-30%	3	2	0	0	0	0	0	0	1
31%-40%	3	1	0	0	1	1	0	0	0
41%-50%	3	1	0	1	1	0	0	0	0
51%-60%	4	1	0	0	1	0	0	0	0
61%-70%	7	2	1	0	3	1	0	0	0
71%-80%	6	0	0	0	2	1	0	1	1
81%-90%	7	1	0	0	1	3	0	1	1
91%-100%	85	11	4	3	19	23	3	2	12
All	123	19	7	4	28	29	3	4	16
Average Production Cost									
Less than $200	16	2	1	0	3	2	2	2	1
$201-$250	44	10	4	0	7	12	1	0	6
$251-$350	45	5	2	2	12	10	0	3	6
$351-$450	11	1	0	2	3	2	0	0	2
$451-$550	5	0	0	0	2	2	0	0	1
$551-$650	2	1	0	0	0	1	0	0	0
All	123	19	7	4	27	29	3	5	16
2 common and Lower Lumber %									
Below 35%	11	1	2	0	0	4	0	0	1
36%-40%	38	3	1	3	12	9	1	1	7
41%-50%	39	7	1	0	11	9	1	2	4
51%-60%	18	4	2	1	2	3	1	0	3
61%-65%	7	0	1	0	3	0	0	1	1
More than 65%	11	4	0	0	0	4	0	1	0
All	124	19	7	4	28	29	3	5	16

Table 4-8: Sawmill willingness to collaborate with other stakeholders by various demographic measures.

		Collaboration with other SM		Ready to share grader		Can share production information		Collaborate with the third party		Accept investment in collaboration	
	N	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Production Capacity											
Below 10 MMBF	70	18	51	32	37	20	49	17	52	26	43
10 to 15 MMBF	25	1	23	7	17	2	22	2	22	4	20
16 to 20 MMBF	8	2	5	2	5	1	6	0	7	2	5
21 to 25 MMBF	6	2	4	2	4	3	3	3	3	2	4
26 to 30 MMBF	6	2	4	2	4	2	4	0	6	0	6
31 to 35 MMBF	3	0	3	3	0	0	3	0	3	1	2
More than 35 MMBF	6	1	5	3	3	2	4	1	5	0	6
All	124	26	95	51	70	30	91	23	98	35	86
HW Production Volume %											
0%-10%	2	2	0	2	0	2	0	1	1	2	0
11%-20%	3	0	3	2	1	1	2	0	3	1	2
21%-30%	3	0	3	0	3	0	3	0	3	1	2
31%-40%	3	0	3	0	3	0	3	0	3	0	3
41%-50%	3	0	3	1	2	0	3	0	3	0	3
51%-60%	4	3	1	2	2	3	1	3	1	1	3
61%-70%	7	2	5	4	3	3	4	3	4	3	4
71%-80%	6	1	5	2	4	2	4	1	5	3	3
81%-90%	7	4	3	4	3	4	3	2	5	1	6
91%-100%	85	14	69	34	49	15	68	13	70	23	60
All	123	26	95	51	70	30	91	23	98	35	86
Average Production Cost											
Less than $200	16	6	10	9	7	5	11	6	10	9	7
$201-$250	44	9	35	18	26	14	30	9	35	13	31
$251-$350	45	5	38	15	28	6	37	5	38	10	33
$351-$450	11	3	7	4	6	3	7	3	7	1	9
$451-$550	5	2	3	3	2	1	4	0	5	1	4
$551-$650	2	1	1	1	1	1	1	0	2	1	1
All	123	26	94	50	70	30	90	23	97	35	85
2 common and Lower Lumber %											
Below 35%	11	5	6	7	4	7	4	6	5	7	4
36%-40%	38	9	29	18	20	8	30	7	31	11	27
41%-50%	39	3	34	12	25	6	31	5	32	8	29
51%-60%	18	4	14	6	12	3	15	2	16	4	14
61%-65%	7	1	6	3	4	2	5	1	6	2	5
More than 65%	11	4	6	5	5	4	6	2	8	3	7
All	124	26	95	51	70	30	91	23	98	35	86

Table 4-9: Resources required by sawmills to begin production of SGHL

Particular		Equipment		Certified Grader		Sorting capacity		Kiln capacity		S4S planer		Lumber Storage	
	N	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Production Capacity													
Below 10 MMBF	70	38	27	14	51	25	40	21	44	9	56	25	38
10 to 15 MMBF	25	19	6	13	12	15	10	14	11	9	16	15	10
16 to 20 MMBF	8	3	5	1	7	1	7	3	5	1	7	1	7
21 to 25 MMBF	6	1	4	0	5	1	4	1	4	1	4	2	3
26 to 30 MMBF	6	4	1	2	3	3	2	2	3	1	4	2	3
31 to 35 MMBF	3	2	1	2	1	1	2	1	2	0	3	2	3
More than 35 MMBF	6	4	2	3	3	5	1	4	2	3	3	4	2
HW Production Volume %													
0%-10%	2	0	0	0	0	0	0	0	0	0	0	0	0
11%-20%	3	2	0	2	0	2	0	2	0	2	0	2	0
21%-30%	3	1	2	0	3	0	3	0	3	0	3	0	2
31%-40%	3	2	1	2	1	2	1	2	1	1	2	2	1
41%-50%	3	3	0	3	0	2	1	3	0	2	1	3	0
51%-60%	4	2	2	2	2	2	2	2	2	2	2	3	1
61%-70%	7	5	1	1	5	4	2	1	5	1	5	4	2
71%-80%	6	4	2	2	4	2	4	2	4	1	5	2	4
81%-90%	7	5	2	1	6	2	5	4	3	1	6	3	4
91%-100%	85	47	35	22	60	35	47	30	52	14	68	32	49
Average Production Cost													
Less than $200	16	9	5	3	11	7	7	4	10	1	13	4	9
$201-$250	44	29	13	15	27	23	19	20	22	12	30	24	17
$251-$350	45	22	21	11	32	14	29	15	28	6	37	16	27
$351-$450	11	6	4	3	7	5	5	4	6	3	7	4	6
$451-$550	5	3	2	2	3	1	4	2	3	1	4	2	3
$551-$650	2	1	1	0	2	0	2	0	2	0	2	0	2
2 common and Lower Lumber %													
Below 35%	11	6	2	3	5	4	4	2	6	2	6	4	4
36%-40%	38	21	16	9	28	14	23	15	22	8	29	10	25
41%-50%	39	22	16	11	27	19	19	14	24	8	30	18	20
51%-60%	18	13	5	6	12	7	11	10	8	2	16	10	8
61%-65%	7	4	3	2	5	4	3	3	4	1	6	5	2
More than 65%	11	5	4	4	5	3	6	2	7	3	6	4	5

4.2.5 **Measuring the Current Ability of Sawmills**

Sawmills were asked to indicate additional resources needed, based on current resources and existing lumber production technology. The RI value was calculated based on the sawmill's response to the additional resources required to begin producing SGHL. Each of the requirements and expectations to manufacture SGHL was explained in section two of the questionnaire. So, it was assumed that the respondents were aware of their sawmills' additional needs based on current practices. Table 4-10 explains the RI value and its meaning based on sawmill responses. The distribution of the observed RI-value based on various demographic measures are summarized in Table 4-11.

Table 4-10: RI value and corresponding meaning to interpret sawmills requirements

RI Value	Resources
6	No additional resources required
5	Required at least one resource
4	Required at least two resources
3	Required at least three resources
2	Required at least four resources
1	Required at least five resources
0	All types of resources required

4.2.6 **Interpretation of RI**

The surveyed sawmills' RI value is used to justify the additional investment required by the sawmills to begin producing SGHL. Based on the sawmills' production capacity, out of 70 sawmills, 28% of the sawmills with a production capacity of less than 10 MMBF required all the resources to produce SGHL. An additional 25% of the sawmills required investing in at least one resource, and 17% needed at least two resources. Around 9% of these sawmills had all the necessary resources to begin the production of SGHL. Out of 25 sawmills with production capacities of 10 to 15 MMBF, 24% of the sawmills required all types of resources, and 28% of these sawmills were ready to begin production of SGHL with no additional investment. Of sawmills with production capacity higher than 20 MMBF, only three sawmills could begin SGHL production without additional investment. Most others required up to five various resources. Most of these sawmills required certified graders, 4-side planers, and additional kiln capacity to produce SGHL.

Table 4-11: Observed the current ability index of the sawmills by various demographic measures.

	RI Value							
	N	0	1	2	3	4	5	6
Production Capacity								
Below 10 MMBF	70	20	17	9	12	5	1	6
10 to 15 MMBF	25	6	1	1	4	2	4	7
16 to 20 MMBF	8	3	4	0	0	0	0	1
21 to 25 MMBF	6	3	1	1	1	0	0	0
26 to 30 MMBF	6	2	1	0	1	1	0	1
31 to 35 MMBF	3	0	1	0	1	1	0	0
More than 35 MMBF	6	1	0	1	0	1	1	2
All	124	35	25	12	19	10	6	17
HW Production Volume %								
0%-10%	2	2	0	0	0	0	0	0
11%-20%	3	1	0	0	0	0	0	2
21%-30%	3	2	1	0	0	0	0	0
31%-40%	3	1	0	0	0	0	1	1
41%-50%	3	0	0	0	0	1	0	2
51%-60%	4	1	0	1	0	0	1	1
61%-70%	7	2	1	0	3	0	0	1
71%-80%	6	1	2	1	1	0	0	1
81%-90%	7	1	2	2	0	1	0	1
91%-100%	85	23	19	8	15	8	4	8
All	123	34	25	12	19	10	6	17
Average Production Cost								
Less than $200	16	5	3	3	3	1	0	1
$201-$250	44	11	5	4	9	2	3	10
$251-$350	45	13	12	4	6	6	2	2
$351-$450	11	3	4	0	1	0	0	3
$451-$550	5	2	0	1	0	1	1	0
$551-$650	2	1	1	0	0	0	0	0
All	123	35	25	12	19	10	6	16
2 common and Lower Lumber %								
Below 35%	11	3	2	1	4	0	1	0
36%-40%	38	10	14	2	1	4	2	5
41%-50%	39	12	6	4	6	2	2	7
51%-60%	18	3	2	2	6	3	0	2
61%-65%	7	1	1	1	2	1	0	1
More than 65%	11	6	0	2	0	0	1	2
All	124	35	25	12	19	10	6	17

Most of the sawmills with a production capacity of 10 million bf to 25 million bf per year had a RI value higher than three. These sawmills accounted for approximately 47%, and few of them has RI value of six.

Most of the sawmills with a production capacity of less than 10 million bf had an RI of less than three. Fifty-three percent of the sawmills could process both softwood and hardwood logs with an RI value of six. Only 33% of the sawmills with an RI value of five could saw both hardwood and softwood.

Seventy percent of the sawmills with an RI value of six had a lower volume of the 2 common and lower-grade lumber. Only 11% of the sawmills had up to 60% of 2 common and lower-grade lumber by volume. Sixty-five percent of the sawmills with an RI value of six also had lumber production costs below $350 per 1000 bf of lumber. Only 12% of the sawmills had production costs higher than $450.

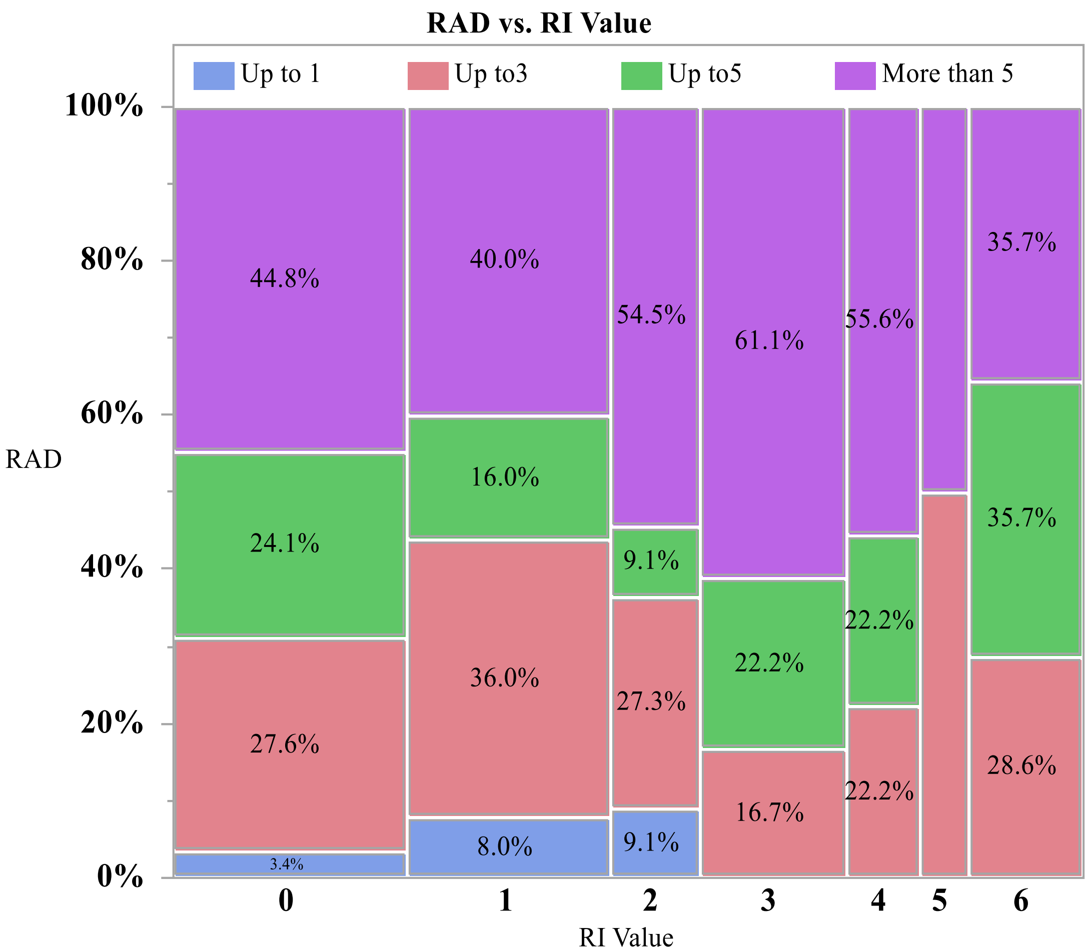

Figure 4-6: RI-value recorded for required minimum annual demand of SGHL to begin production

Based on the required minimum annual demands (RAD) of SGHL, 35.7% of sawmills with an RI value of six expect annual demand to be more than 5 million bf. Another 35.7% expect between 3 to 5 million bf to begin the SGHL production. None of the sawmills with RI value higher than three would consider producing the SGHL if the annual demand was less than 1 million bf. The detail of the distribution is presented in Figure 4-6.

There were 31.3% of sawmills with an RI value of 6 who said the expected minimum revenue or required hardwood lumber value (RHLV) from SGHL should be five to ten percent higher than NHLA grade lumber. However, 50% of the sawmills responded that they would produce the SGHL if the revenue were equal to the NHLA grade lumber. The detail of the distribution is presented in Figure 4-7.

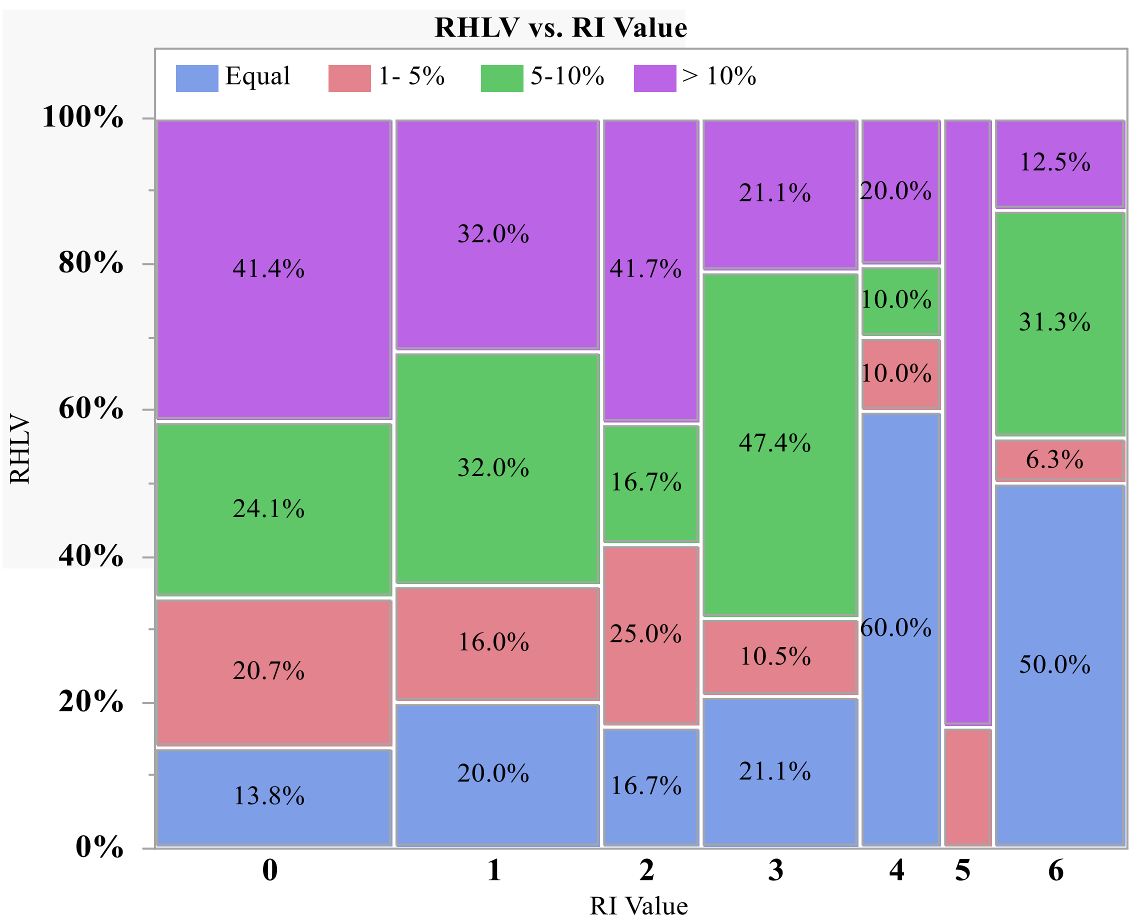

Figure 4-7: RI value of the sawmills and required minimum value of the SGHL.

Out of 124 sawmills, 65% of the sawmills with an RI value of six knew about the SGHLs, but only 35% of them knew about grading rules by various agencies. It is interesting to note that many sawmills with lower RI values were aware of this potential market and the grading rules. Around 40% of the sawmills responded that they employed a grader capable of grading hardwood lumber with structural grading rules. Forty-seven percent of the sawmills with an RI value of six had employed graders capable of grading hardwood lumber for structural application. The distribution of the RI and sawmill awareness of SGHL is presented in Figure 4-8.

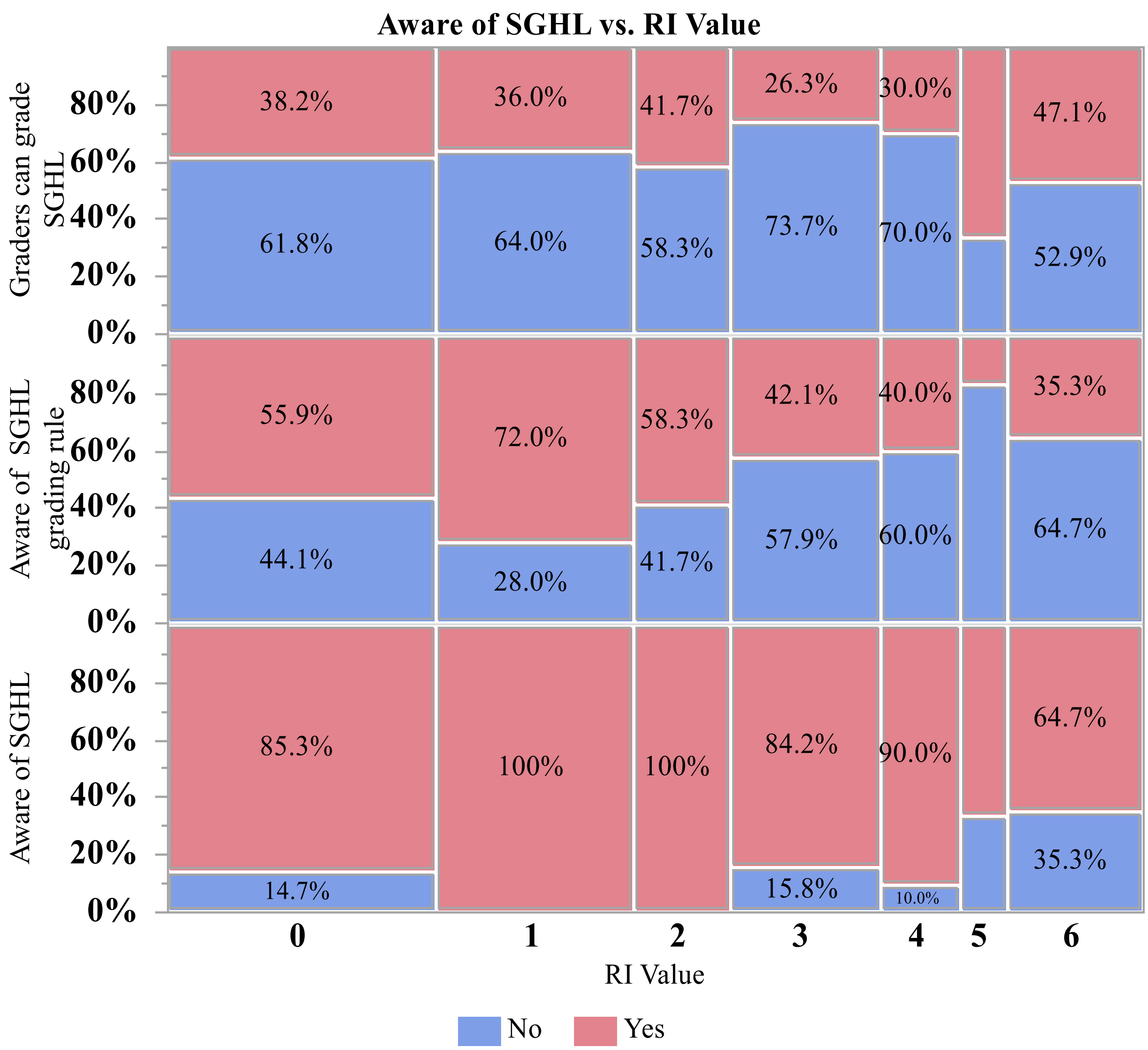

Figure 4-8: RI value of the sawmills distributed by sawmill awareness to SGHL and grading rules.

Out of 124 sawmills, more than 85% of the sawmills could saw SGHL and reprocess cants to produce SGHL. Only 35% of the sawmills with an RI value of six had a 4-side planer, and more than 52% of the sawmills had enough kiln capacity. Fifty-nine percent of the sawmills with an RI value of six had adequate kiln capacity. However, only 53% of the sawmills had excess kiln capacity. This observation indicates that around 60% of the sawmills with RI value six and excess kiln capacity were ready to produce SGHL. Sawmills with limited kiln capacity had lower RI values. Fifty-six percent of sawmills with an RI value of zero had adequate kiln capacity. However, only 23.5% had excess kiln capacity. The detail of the distribution is presented in Figure 4-9.

Sawmills would need to adopt different production strategies from their current practices to manufacture SGHL. Sawmills could choose production strategies based on the market and the return from potential new products. Sawmills were asked about their strategies to adopt new production practices based on product value. Most of the sawmills responded that they would adopt mixed grade lumber strategies if the value of new lumber types were higher than 5% compared to current lumber products. For SGHL with values higher than 5%, only 14% of the sawmills with an RI value of six responded that they would continue with NHLA grade lumber production. There were 20% of sawmills with product value below 5% higher than NHLA grade lumber. The detail of the distribution is presented in Figure 4-10 and Figure 4-11.

Most of the sawmills responded that they were opened to collaborating with other hardwood sawmills and lumber distributors. Eighty-two percent and 88% of the sawmills with an RI value of six and five were opened to collaborating with other sawmills and brokers, respectively, to fulfill the CLT industry's lumber demand. Interestingly, only 47% of the sawmills were opened to sharing certified graders to grade SGHL with an RI value of six compared to 60% and 83% of the sawmills with the RI values of four and five, respectively. Approximately 70% of the sawmills with an RI value of six would share production information with CLT industries if necessary, which is also a comparatively lower percentage than sawmills with RI values of four and five.

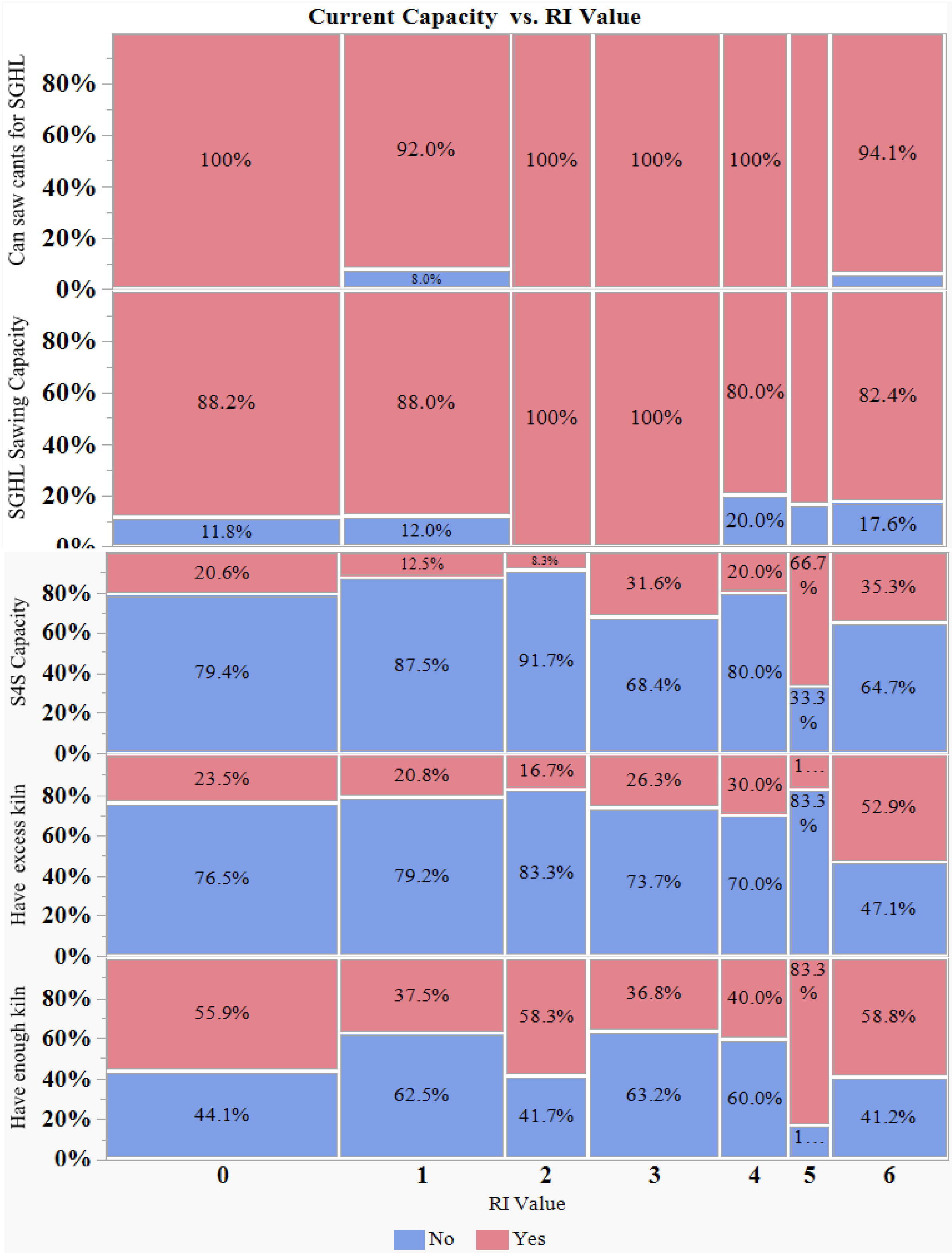

Figure 4-9: Distribution of RI value and kiln capacity of the participating sawmills

Sawmills were asked if they would accept investment from CLT manufacturers to help produce quality SGHL. Most of the sawmills with an RI value higher than three responded that they would accept a collaboration. Of the sawmills with an RI value of six, 76.5% would accept investment from CLT industries. The distribution of RI values and sawmills' willingness to accept CLT industries' investment is presented in Figure 4-12.

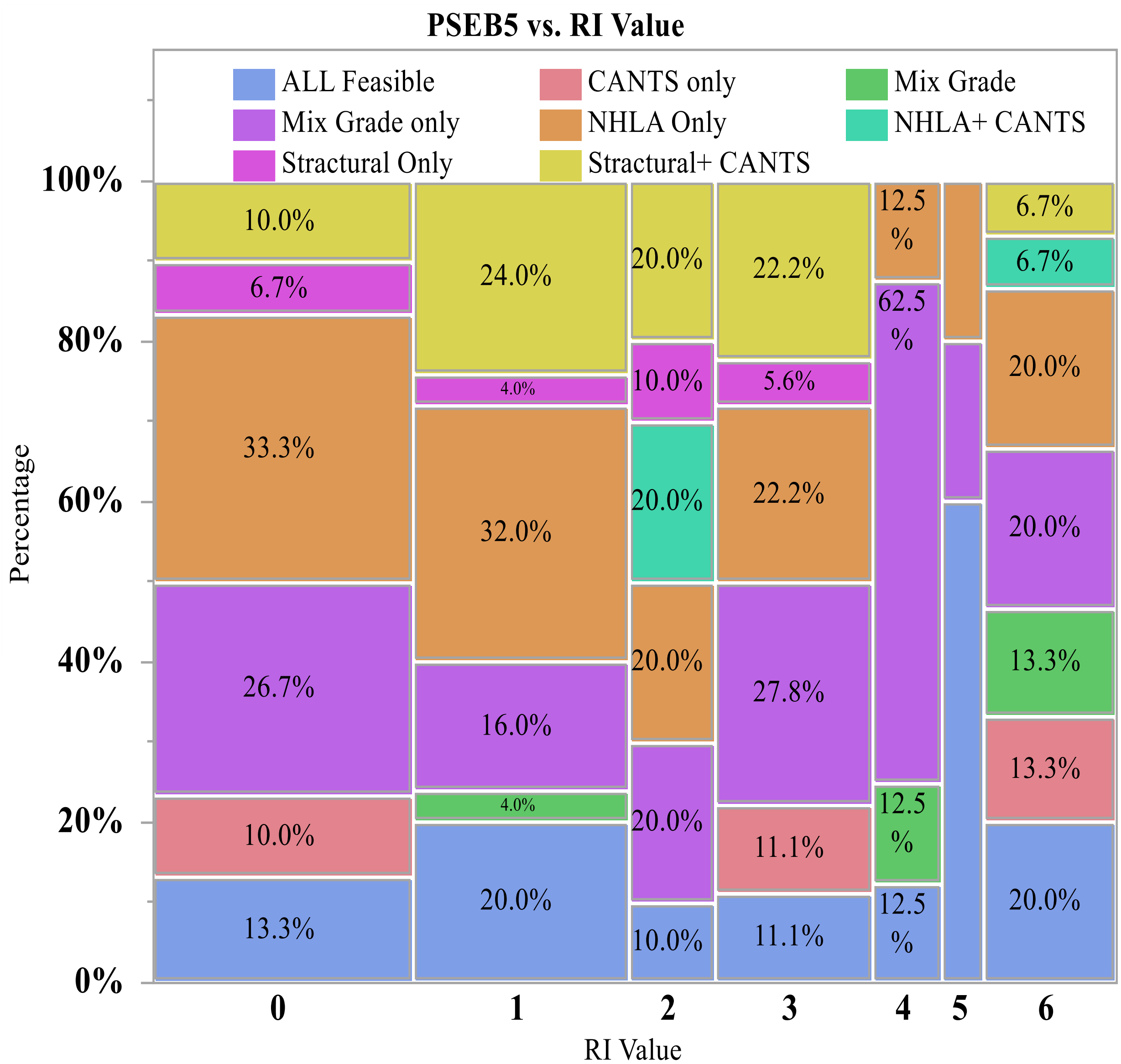

Figure 4-10: RI value of the sawmill and response on production strategies for less than 5% higher SGHL value than NHLA grade lumber.

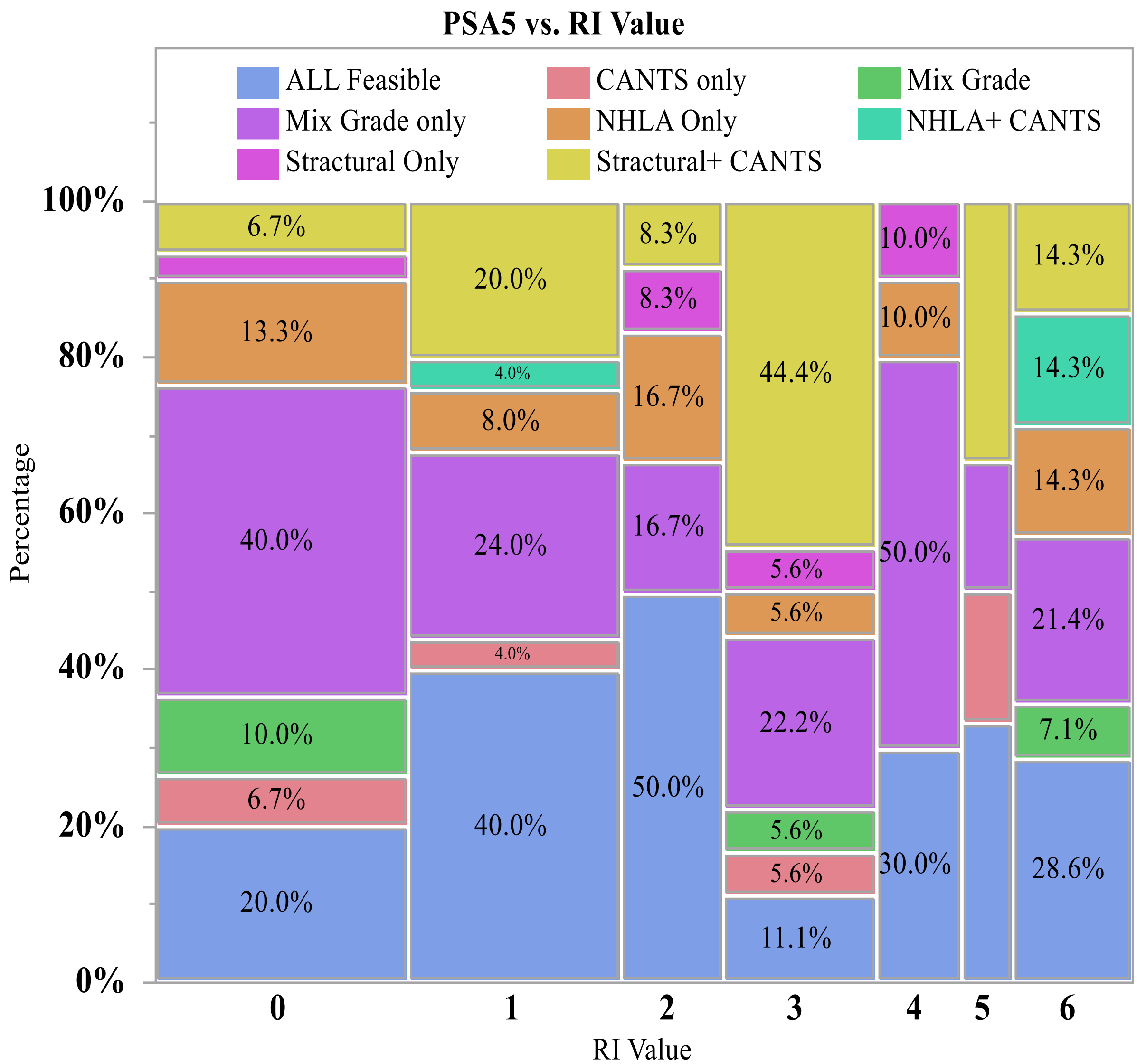

Figure 4-11: RI value of the sawmill and response on production strategies for more than 5% higher SGHL value than NHLA grade lumber.

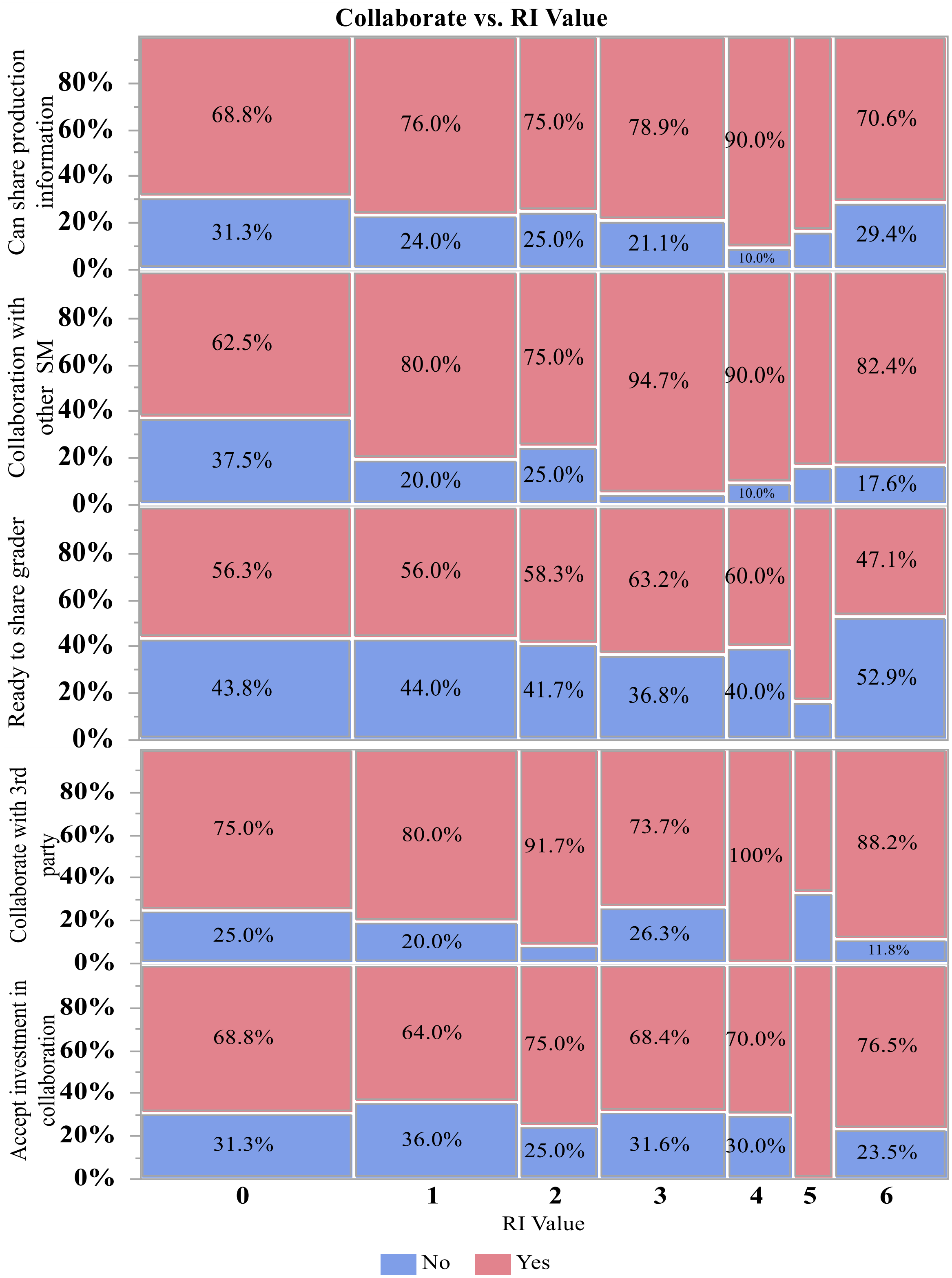

Figure 4-12: RI value of the sawmill and response on potential collaboration.

4.3 Discussion and Conclusions

Out of 2040 sawmills, 124 responded to this survey, most processed red oak (30%), white oak (15 %), and yellow poplar (15%) lumber, which constitutes more than 50% of the hardwood lumber produced in participating sawmills. More than 56% of the sawmills had a production capacity of less than 10 million bf per year. Only 12% of the sawmills had production capacity higher than 25 million bf per year. Thirty percent of the sawmills processed both hardwood and softwood logs, and 70% of the sawmills produced only hardwood lumber. Two common and lower grade lumber accounted for 40% to 60% of total lumber by volume in 46% of the sawmills, whereas 16 % of the sawmills had lower-grade lumber volume higher than 60%. More than 84% of the sawmills had production costs below $350, and 49% of the sawmills had production costs lower than $250 to manufacture 1000 bf of lumber.

Most of the sawmills could saw standard SGHL. Almost all the sawmills could resaw hardwood cants. Only 24% of the sawmills could surface all four sides of the lumber. Only 50% of the sawmills had adequate kiln capacity, and about 27 % of the total sawmills also had excess kiln capacity. Many of them had less than 20% excess capacity of those sawmills with excess kiln capacity.

Approximately 47% of the sawmills would like to see an SGHL demand of more than 5 million bf per year before considering this new product's commercial production. Also, 32 % of the sawmills would like to see an annual demand of up to 3 MMBF. Forty percent of the sawmills would produce SGHL if there were a 5% higher lumber value than NHLA. Also, 32% of the sawmills responded they would switch to new production strategies for more than 10% higher value of SGHL. Another 27% of the sawmills wanted to see 5 -10% higher lumber value than NHLA grade lumber. Almost 86% of the sawmills knew SGHL, and 52% of them also knew about the grading rules of SGHL. Thirty-eight percent of the sawmills employed a grader who could grade hardwood lumber for structural application.

Twenty-six percent of the sawmills did not want to change to the new product if the new product's value was up to 5% higher than NHLA grade lumber. However, only 10% of the sawmills would consider producing NHLA grade lumber if the lumber value were higher than 5% compared to NHLA grade lumber. For a 5% and higher lumber value, 32% of the sawmills chose to produce a mixed grade of lumber, combining it with NHLA grade. In contrast, for below 5% of lumber value, only 28% chose to produce mixed-grade lumber.

Almost 80% of the sawmills were ready to collaborate with other hardwood sawmills. However, only 58% of the sawmills were ready to share employing a certified grader. Seventy-five percent of the sawmills were ready to share production information with CLT industries. More than 80% of the sawmills were ready to collaborate with lumber distributors. Seventy-one percent of the sawmills were ready to accept investment from CLT industries to acquire the required technology and resources to begin producing SGHL.

Around 40% of the sawmills were required to invest in sawing technology and equipment. In contrast, more than 70% of the sawmills needed to hire a certified lumber grader to begin the production of SGHL. Around 60% of the sawmills needed to invest in additional lumber sorting and kiln capacity. Approximately 80% of the sawmills needed to invest in a planer, and 55% needed to invest in additional lumber storage.

This survey found very few sawmills ready to produce SGHL. Commercial production of SGHL required additional investment for most of the sawmills participating in this research. Many sawmills express interest in producing SGHL but were looking for significant demand and advantages over NHLA grade lumber. Sawmills were looking to guarantee that the new product switch would produce a significant return for each additional investment compared to the existing product. This research assumed there was a market for SGHL as CLTs' raw material. However, the potential of SGHL can only be explored if CLT manufacturers are interested in using it on a commercial scale. The first step of successfully implementing SGHL on a commercial scale requires an aggregated plan to produce lumber and a stable market. Additionally, the most crucial factor in promoting SGHL in CLTs will be accepting SGHL in the CLT standard. If hardwood is introduced in the CLT standard, CLT manufacturers and hardwood sawmills will explore production and use.

It is critical to identify the sawmills across the region that could produce SGHL with minimal investments because very few sawmills have all the required resources. These sawmills should work in collaboration with the CLT manufacturer to develop a working protocol to produce SGHL. This protocol must define the minimum quality that can be accepted for CLT use. Sawmills ready to produce SGHL based on their current technology must train their graders to grade SGHL. As each step is completed and both sawmills and CLT manufacturers are confident about SGHL quality and quantity, commercial production can begin. None of the CLT companies are near a pocket region of hardwood. Thus, market access to SGHL is exceptionally complicated, with many obstacles to overcome to compete with existing raw materials. If the CLT manufacturers in Maine and Alabama were to introduce SGHL in CLTs, the hardwood sawmills across the southeastern and northern regions could find access to a new market. This continuously growing market ultimately helps to expand the hardwood lumber market.

Based on the analysis of survey responses, this study concludes that around 10% of the sawmills who participated in this survey are currently ready to produce SGHL and that if the current value of SGHL was 5% or more than two common and lower grade NHLA lumber, more than 90% of the sawmills responded they would produce SGHL as a product mixed. So, the major driver for producing SGHL is the lumber value.

4.4 Summary and Major Findings of the Study

1. The survey was sent to 2040 sawmills, and only 6% of the surveys were completed. This survey found the major tree species sawn at participating sawmills were red oak, yellow poplar, and white oak, which counts more than 50% of lumber production.
2. Approximately 56% of sawmills who participated in the survey had an annual production capacity of less than 10 million bf of lumber. Only about 5% had an annual production capacity higher than 35 million bf, and 26% had a production capacity of between 10 million bf and 20 million bf.

3. Approximately 70% of the participating sawmills produced only hardwood lumber, and the remaining 30% produced both hardwood and softwood lumber. More than 63% of the sawmills that produced both hardwood and softwood lumber were producing at least 50% hardwood lumber by volume.
4. Almost all sawmills could saw SGHL as a product mix, but only 24% of the sawmills could surface all four sides of the lumber, and 50% of them could kiln-dried them.
5. More than 86% of the sawmills were aware of SGHL, and 51% also knew the structural grading rules for hardwood lumber, but only 40% of the sawmills currently employed a grader who could grade both NHLA and structural grade.
6. Twenty-seven percent of the sawmills would require a minimum value of SGHL to be 5% to 10% higher than NHLA grade lumber, and 25% of the sawmills were ready to produce SGHL on a commercial scale for equal value to NHLA grade lumber. The annual demands of SGHL should be higher than 5 million bf for 48% of sawmills to begin the production of SGHL.
7. About 78% of hardwood sawmills could collaborate with other sawmills. Fifty-eight percent of sawmills would share a grader to grade SGHL. Seventy-five percent of the sawmills would share production information with CLT mills to improve product quality, and 71% also would accept investment from CLT industries to produce SGHL.
8. About 40% of the sawmills need to invest in sawing technology, 56% required additional sorting capacity, and 60% needed to invest in kiln capacity. Additionally, 78% of the sawmills required four side planers, and 56% needed to invest in additional lumber storage facilities. More than 70% of sawmills were required to employ a certified SGHL grader.
9. The sawmills' RI value was used to justify the additional investment required by the sawmills to begin producing SGHL. Twenty-eight percent of the sawmills with a production capacity of less than 10 MMBF required all the resources to produce SGHL. An additional 25% of the sawmills required investing in at least one resource, and 17% needed at least two resources. Most of the

sawmills with a production capacity of 10 million bf to 25 million bf per year had a RI value higher than three. Only 33% of the sawmills with an RI value of five were sawing both hardwood and softwood.

10. Seventy percent of the sawmills with an RI value of six had a lower volume of the 2 common and lower-grade lumber. Sixty-five percent of the sawmills with an RI value of six also had lumber production costs below $350 per 1000 bf of lumber.
11. Based on the required minimum annual demands of SGHL, 35.7% of sawmills with an RI value of six were looking for more than 5 million bf of lumber and another 35.7% required an annual demand of 3 to 5 million bf.
12. There were 31.3% of sawmills with an RI value of 6 that needed the SGHL value to be 5-10% higher than NHLA grade lumber. However, 50% of the sawmills with an RI value of 6 were ready to produce SGHL for equal revenue.
13. Out of 124 sawmills, 65% of the sawmills with an RI value of six knew about the SGHLs, but only 35% of them knew about grading rules by various agencies.
14. Eighty-two percent and 88% of the sawmills with an RI value of six were opened to collaborating with other sawmills and brokers respectively to fulfill the lumber demand of the CLT industry, though, only 47% of the sawmills were opened to sharing certified graders to grade SGHL.

CHAPTER 5. STRUCTURAL GRADE HARDWOOD LUMBER ECONOMIC FEASIBILITY

5 Introduction

Softwood species primarily dominate structural lumber markets, but some hardwood species were used in the past. Most of the softwood lumber is produced from pine, cedar, Douglas fir, and spruce trees. It is available in three major categories, structural, yard, shop, and factory. Structural grade softwood lumber is the primary lumber type used in the construction industry. In the US, 38.41 billion board feet (bf) of softwood lumber was consumed in 2017, and only 24.4 billion bf of softwood lumber was produced in the same period (Howard et al., 2018). Thus, the US has a deficit of more than 35% of softwood lumber.

The light-frame structure is the conventional method adopted by the housing industries, the major consumer of structural grade lumber. A light frame structure is limited to a structure of five stories. The growth of mass timber construction also expanded the use of structural lumber. According to The Beck-Group (2018), among all mass timber producers, CLT industries will be the primary consumers of the structural grade lumber by 2025. It is estimated that the CLT industries will consume more than 17% of the total lumber production volume of 2017 in 2025. A noteworthy fact is that mass timber construction does not compete with light-frame structures and is commonly used to construct mid-rise or high-rise structures. So, the growth of mass timber products adds additional demand for structural grade lumber.

Mass timber products' continuous growth provides a new avenue to expand structural grade lumber production from hardwood species. In 2017, 7.87 billion bf of hardwood lumber was consumed in the US, and 8.32 billion bf of hardwood lumber was produced (Howard et al. 2018), so there is a surplus of hardwood lumber in the domestic market. Species like yellow poplar (Liriodendron tulipifera), red oak (Quercus rubra), and white oak (Quercus alba) are adequately available in the northeastern and southeastern regions of the US. Harvesting these species to produce structural grade hardwood lumber (SGHL) can expand the hardwood species' domestic lumber market. SGHL from domestic species reduces the import of structural grade lumber. However, commercial SGHL production must establish a suitable and economical method for existing sawmills (Denig et al. 1984; Koch et al. 1986; Allison et al. 1987).

The mechanical properties, also known as allowable structural grade lumber properties, are the major factors considered for structural application. Allowable lumber properties are the strength properties assigned to fiber stress in bending, tension parallel-to-grain, horizontal shear, compression parallel-to-grain, and compression perpendicular-to-grain. When uniform lumber manufacturing procedures were first implemented to grade structural lumber in the 1920s, the lumber's allowable properties were assigned for both softwood and hardwood species (Green et al., 2001). Allowable properties for hardwood species were also included in the first edition of the National Design Specification (NDS) published in 1944. However, the following edition of the NDS excluded hardwood species. Studies on production technology, the economics of the yield, and the potential market of SGHL from different hardwood species were published in the 1970s and 1980s. After various studies concluded the feasibility of SGHL, the NDS again included design values for some hardwood species in the 1988 revision (DeBonis et al., 1988).

Although the NDS had included the design values for hardwood species and various studies published results to help in the production of SGHL, and commercial production was limited to a few species. Researchers like Green (2005) and Grasser (2015) pointed out two significant reasons to limit SGHL production on a commercial scale. The first limiting factor is the lower market acceptance of SGHL compared to softwood lumber of similar specifications. The second factor is the lower profit margin for sawmills. Thus, the critical factor in considering producing SGHL is selecting a species that can compete with softwood lumber value and have similar mechanical properties.

Many studies published in the 1970s and 1980s chose yellow poplar (YP) as the dominant species to manufacture SGHL. Yellow poplar is the only species commercially available as SGHL and is commonly used to manufacture trusses (Green, 2005) and laminate veneer lumber (LVL). Yellow poplar exhibits similar properties to softwood, so it has been used for structural application. Additionally, lumber from YP is more competitive with softwood lumber, which is essential for production on a commercial scale (Grasser, 2015).

Production of SGHL on a commercial scale requires a subtle analysis of the production technology, economic feasibility, and market sustainability. There were numerous research projects on production technology and the economic feasibility of SGHL from various hardwood species. However, the absence of a sustainable market for SGHL was the first deterrent. None of the current hardwood sawmills produced SGHL on a commercial scale in the absence of a market. Mass timber construction has emerged as a potential market for SGHL in recent years. Cross-laminated timber (CLTs) is considered a significant market opportunity for suitable lumber grades from some hardwood species. It is crucial to evaluate the technical and economic feasibility based upon the current market potential of SGHL from various species for CLT application.

Commercial production of SGHL requires an attractive return above the current market value of NHLA grade lumber. Sawmills are required to identify the economic advantages of the process and the product. The standard method to evaluate the yield and revenue of a new production method in sawmills is the log yield study (Green, 2005). The yield and revenue analysis to produce SGHL can be evaluated based on previous studies. However, a thorough review of the technology and revenue analysis is critical. The last time a log yield analysis of hardwood species was published was in the mid-1990s, was almost 25 years ago. The market and production technology have changed a lot in the last 25 years. A significant shift in the lumber market was seen after the 2008-2009 global recession. Thus, it is essential to review major studies and test results in current practice to implement SGHL production.

Production of SGHL from hardwood species has been studied based on three different practices. One of the first methods was to produce structural lumber from whole logs Denig et al. (1984). Allison et al. (1987) introduced the alternative practice of sawing NHLA grade lumber from logs' outer quality zone and sawing structural lumber from the logs' core. A third method was proposed by Koch et al. (1986) to develop comparable grading between hardwood and softwood lumber grades. Hardwood graded with NHLA rules could be re-graded with a hardwood-softwood comparison table for structural use. For all methods discussed here, selection of the hardwood species, log quality, the economics of the new products, and the appropriateness of technology at modern sawmills are critical for implementing SGHL on a commercial scale.

The first step in producing SGHL from hardwood species is identifying the right log species and log grade. The species selection depends on various factors like availability of logs, the current market for lumber from the species, the species' lumber value, and many other considerations specific to sawmills. Log quality is another factor, as higher-quality logs cost significantly more and potentially yields higher-grade lumber (Ringe 1988). Higher grade lumber is not suitable for producing commercial CLTs because of the higher material cost (Grasser, 2015); due to the value, it fails to compete with softwood CLTs. Higher grade NHLA lumber potentially recovers more revenue than SGHL grade of the same type, given the current lumber value. Thus, sawmills are not interested in producing SGHL from higher-grade logs and losing revenue. Due to these factors, the focus should be on lower grade logs. Ringe (1988) presented similar conclusions after studying the feasibility and competitive nature of YP structural lumber using value-added analysis. Ringe (1988) further concluded that, as log grade declines, log costs decrease faster than the lumber's value, which justifies that SGHL production from low-grade logs is more appropriate than higher grade logs.

Alternatively, SGHL can be produced from cants available in the market. SGHL from cants allows sawmills to recover most of the lower grade lumber for higher-value products because most of the lower grade lumber is produced from the log-center from where cants are primarily manufactured (Allison et al.,1987). Allison et al. (1987) introduced a new sawing method for producing SGHL from hardwood logs, allowing sawmills to produce NHLA grade lumber from the logs' outer zone, leaving cants. These cants were resawn to the SGHL dimension, and the economics of the process were evaluated. McDonald et al. (1996) also determined the structural grade yield from freshly sawn heart-centered cants from various hardwood species. McDonald et al. 's (1996) experiments concluded that the cants' source influenced all species' structural lumber yield. So, the percentage of higher-grade SGHL depends on the log grade used to produce the cants.

Structural grading of hardwood lumber produced from the lower grade logs or cants should exhibit acceptable mechanical properties. Faust et al. (1990) tested the mechanical properties of structural grade lumber produced from YP cants. These cants were manufactured as pith center cants by sawing the logs to produce rectangular cants whose cross-sectional diagonals intersect at the center of the log pith on both faces across the diameter. Mechanical test results from Faust et al. (1990) comfortably exceeded the minimum design value of visually graded YP lumber for all lumber grades mentioned in the NDS 2012 edition supplement.

One of CLT manufacturers' limitations for using hardwood lumber from the CLT mills surveyed in chapter 3 of this study is the lumber's moisture content. Drying the lumber is critical for CLT manufacturing because the procedure adopted to dry lumber has a considerable influence on the lumber's mechanical and physical properties. Improper drying significantly reduces the lumber's strength and may cause splitting, crooking, or waning on the surface (Denig et al. 1984). Saw-Dry-Rip (SDR) technology was recommended by Denig et al. (1984) to reduce the lumber's physical deformation during production and drying. Furthermore, SDR technology was also used by researchers Maeglin et al. (1983) and Allison et al. (1987) in their corresponding log yield study using hardwood logs.

Allison et al. (1987) compared the value recovery in a yield study to saw SGHL from cants after sawing NHLA grade lumber from the outer zone. This mixed lumber production yielded higher revenue compared to producing only NHLA grade lumber production from the process. Mostly 2B common and lower grade lumber was converted into SGHL. On the referenced lumber value, a mixed grade revenue was higher than only producing NHLA grade. Koch et al. (1986) also compared the economics of buying 4/4" and 5/4" yellow-poplar FAS and Number 1 Common hardwood factory lumber to replace factory select structural lumber and indicated that a hardwood sawmill could yield more revenue by manufacturing structural lumber.

In summary, the literature indicates that the lumber value of SGHL depends upon various factors, including the lumber thickness and grade. Higher grade lumber is not suitable for producing commercial CLTs because of higher material costs (Grasser, 2015). Longer lumber has a higher lumber value per bf for structural grade lumber. The quality of logs or cants is the primary factor in recovering higher-grade SGHL (Ringe,1988 & McDonald et al., 1996). For higher revenue from SGHL, the lumber's length and lumber grade have significant influence. Hence, it is crucial to evaluate the revenue based on log length, log quality, and log diameter. The economics of SGHL production at modern sawmills based on log length, log diameter, and log quality require a reassessment of past yield studies.

There is a limitation of the yield study discussed in the literature to evaluate log yield based on log length, diameter, and log quality(grade). Denig et al. 's (1984) yield equation excluded the log length in analysis, limiting eight-feet-long logs with various diameter ranges. Thus, the study only aids in understanding the methods' appropriateness but does not help predict actual yield based on the grade and dimension of the logs, except eight-feet lengths. Allison et al. (1987) did not mention the length of the logs and log grades used for their experiment. They excluded logs with a diameter greater than 12 inches. Their study also falls short of predicting the log yield based on log dimension and quality.

The major limitation of the Faust et al. (1990) study was Select Structural, and Number 1 grades that were not separated and graded as No. 1 and better. Also, the log grade used to produce cants for this experiment was unknown. Moody et al. 's (1993) log yield study also did not report the number of logs or the sawing procedure to obtain structural grade lumber. Whether the whole log was sawn to obtain structural grade lumber or only cants were sawn to get structural grade lumber was not mentioned. Additionally, the industrial-grade lumber (economy grade) volume was not reported and excluded. Thus, observed results only explain the partial log yield from the log grade.

McDonald et al. 's (1996) log yield study focused on resawing cants. However, the cants' quality depends on the grade of the log processed, Ringe (1988). Thus, the yield observed from this experiment excluded the log grade, which is critical information for economic recovery. Higher grade logs cost more than lower grade logs, but the lumber value is independent of the log grade and based only on the lumber grade. Thus, sawmills need information on lumber yield based on log grade and dimension for maximized economic recovery.

Recently, there have not been many studies on hardwood logs for structural use. The value of the logs and lumber have changed with the changing market. Based on previous yield studies, the actual yield of mixed lumber production to produce 6" and 8" wide structural lumber from the hardwood species' core is hard to evaluate at the current value. None of the previous log-yields studied considered only producing 6" and 8" wide lumber to compare the economics. Lumber measuring 2" x6" and 2" x8" from softwood was the CLT manufacturers' primary choices, as observed from the CLT mill survey from Chapter 3 of this study. Thus, 6" and 8" wide SGHL was considered the primary product type from hardwood species for CLT application. This study's objective was to evaluate the feasibility of mixed grade lumber production from modern sawmills. The log sawing method used was like Allison et al. (1987), with minor changes in the sawing process. Allison et al. 's (1987) method was chosen because higher-grade lumber is economically less competitive to use in CLTs. Their method was appropriate for producing higher-grade lumber from the outer zone and leaving cants for SGHL production. This study's specific objective was to compare the revenue between control (visually graded NHLA) logs and test (mixed; NHLA +NELMA) hardwood log samples. This study's novelty is the log-yield results based on the logs' diameter, length, and USDA grade.

5.1 Methodology

The overall study was constructed as a case study and designed using the framework discussed in Chapter 3. This study was completed with two log yield studies. The first log yield study was completed as a pilot study and the second one as a full-scale study. The case study components for this study are discussed in detail in the following sections.

5.1.1 Research Question

The research question for this case study was:

"What is the economic advantage of hardwood sawmill operations for producing 2" x6" and 2" x8" structural grade lumber as a product mix from low grade hardwood logs?"

5.1.2 Research Purposes

Sawmills must adopt a new sawing practice to manufacture SGHL from hardwood logs. Sawmills must see higher profits because of switching to the new process. This research was developed to study low-grade hardwood logs' ability to produce both NHLA and SGHL and compare their economic feasibility. SGHL produced from this yield study is considered as a potential raw material for the CLT industries. Thus, this log yield study aims to promote the production of SGHL as CLT raw material and increase the use of domestic lumber.

5.1.3 Units of Analysis

Log yield research requires time and resources from participating sawmills. Many sawmills contacted denied co-operating with the new production adjustments at the expense of the sawmills' resources and time. Additionally, lumber produced by sawmills is based on market demand. The actual dimensions of the lumber produced from this study have a limited market. After multiple requests and follow-up, two sawmills, one in Virginia and another in West Virginia, accepted the request to saw lumber from the desired logs. The sawmill from Virginia produces both hardwood and softwood lumber, and this company was chosen to complete the pilot study. The full-scale yield study was completed with the sawmill from West Virginia for the selected log grade group. The sawmill from West Virginia agreed to saw 8/4" thick lumber instead of 6/4" lumber because of the higher market value. The 8/4" thick lumber is also the accepted thickness for the CLT application (PRG 320,2019), so the agreement was made to run the full-scale log yield study.

5.1.4 Linking Findings to Research Purpose

The research purpose of this log yield study is to promote the use of SGHL in CLTs production. The economic comparison of mixed grade lumber production and only NHLA grade lumber production was observed. The results are the guidelines for sawmills to select log species, grade, and dimensions to produce SGHL. Additionally, based on this log yield study results, the economics of converting low value hardwood lumber to a CLT raw material was determined. The results were utilized to quantify the production cost of structural lumber from low value hardwood logs. Structural grade lumber for CLT application should be surfaced on all four sides, dried to a moisture content of 12±3%, and trimmed and ripped to standard dimensions. All of these processes add value to the product. Identifying the cost of additional value-added work was critical to estimate lumber value for the sawmill. Additionally, this case study's results were utilized to obtain hardwood CLT production costs and revenue analysis.

5.1.5 Research Methodology

The study's overall process is shown in Figure 5-1 and completed in three steps. First, a pilot study of the proposed log yield was conducted. In the second step, a log yield study was completed. Finally, using the log yield data, the economics of SGHL as a product mix were evaluated.

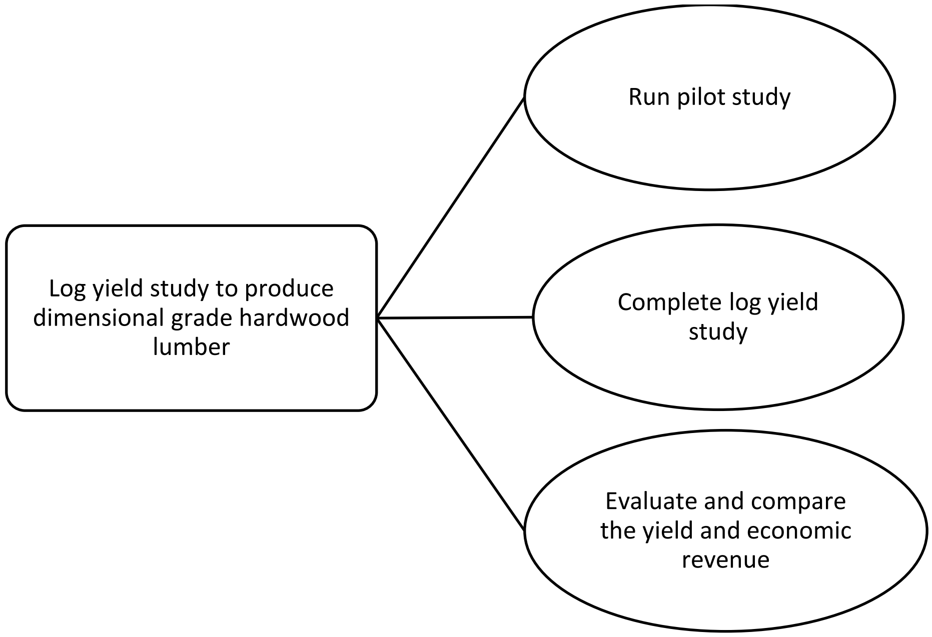

Figure 5-1: Overall process adopted to complete the log yield study.

5.1.6 **Pilot Study**

The log yield study tested a new sawing procedure to produce SGHL, which required both resources and time. A pilot log yield study was designed to develop a research protocol, streamline the method, and collect preliminary data to test the main objectives. As discussed by McConnell et al. (1994) and Polit et al. (2001), a pilot study's primary objective is to test a research instrument's feasibility. A pilot study was conducted as a small-scale version of the main project through trials to prepare the study. Hardwood sawmills were not producing SGHL, so they needed to define a new process to handle the logs and lumber. Material handling is crucial for a log yield study as all logs and lumber need to be tracked and marked throughout the process. The pilot study was critical in identifying the problematic areas, following research protocols, and possible yield study failures. The pilot study also tested the proposed method and instrument appropriateness and determined the full-scale study (Van et al., 2001). The second aspect of the proposed log yield study was to compare the economics of the new sawing method to produce SGHL from the log core. Thus, this pilot study's objective was to test the new sawing procedure and develop a material handling protocol while tracking the required information. Additionally, this pilot study measured the new sawing method's process feasibility and compared the new process's economics with existing practices.

5.1.6.1 Sample selection for the pilot study

The first step of the log-yield study was to choose a log species. The log species was chosen by considering four significant factors; properties of the lumber to be used in CLTs, current production volume percentage at the sawmill, design value comparison of the hybrid and hardwood CLTs using identified lumber species, and the lumber value. The details of each factor are discussed in the following paragraphs.

Factor 1: Properties of the lumber to be used in CLTs

Hardwood CLTs (HCLTs) were manufactured in the US as a customized product by two manufacturers. The species identified by the CLT manufacturer in Chapter 3 of this study were chosen as the potential species. Hardwood species previously used by CLT manufacturers were red oak, white oak, beech, hickory, maple, and other locally available random species. As neither manufacturer was in the eastern region, one of the dominant species in the eastern region, yellow poplar, was not used in CLTs for commercial purposes in the US. Yellow poplar has been touted as a suitable lumber species by researchers like Beagley et al. (2014), Mohamadzadeh et al. (2015), and Grasser (2015); thus, it was also considered for this evaluation.

The published design values for identified hardwood species were referenced from the NDS 2015 handbook. All five species, red oak, white oak, beech, red maple, and yellow poplar, identified for the log yield study, had strength values for SGHL. The species identified for the log yield study and respective strength properties are presented in Table 5-1. Each of the species has higher strength values than are required for CLT use.

Factor 2: Current production volume percentage at the sawmill

Another factor considered in choosing a log species was the current production percentage of lumber in the sawmills. The data obtained from the hardwood sawmill survey from Chapter 4 was used to identify the top five log species sawn at sawmills. The current production volume for the various hardwood species is presented in Table 5-2 Beech was not in the top five species sawn, based on survey data, and was excluded from further analysis.

Table 5-1: Strength value of structural grade hardwood species; Source: NDS 2015

	Specific Gravity (sg)		*Bending MOR (lbf/in2)*		*Bending MOE (lbf/in2) x 106*	
Species	Min	Max	Min	Max	Min	Max
Red oak	0.59	0.69	10875	18125	1.49	2.27
White oak	0.63	0.88	10295	18415	1.02	1.98
Beech	0.6	0.64	14355	14935	1.37	1.72
Maple	0.48	0.63	8845	15805	1.14	1.82
Yellow Poplar	0.42	0.43	9860	10150	1.45	1.58

Table 5-2: Current Lumber production volume in hardwood sawmills by species; Source: HMR, 2017 and Indiana forestry report, 2017.

	Sawn %	*Average lumber value ($)*	
Species		Mid-West (2017)	Appalachian (2017)
Red Oak	29.9%	545	560
White Oak	15.0%	540	560
Yellow Poplar	15.6%	270	310
Hard Maple	9.4%	450	545
Soft Maple	8.7%	400	540
Beech	--	280	300

Factor 3: Design value comparison of hybrid and hardwood CLTs

It is essential to know the impact of new lumber species in the CLT layers when designing a CLT structure. The new lumber types in CLT manufacturing required a detailed analysis of CLT elements. There are four different analytical design methods (FPInnovations, 2011) for CLT elements, which are listed as,

1. Mechanically Jointed Beams Theory (Gamma Method)
2. Composite Theory (k Method)
3. Shear Analogy Method (Kreuzinger, 1999)
4. Simplified Design Methods

The current version of the CLT standard PRG 320 recommended using the shear analogy method to estimate the CLT panels' shear deformation. The engineering formula used to obtain the CLT's design value was adopted from PRG 320 and is shown in Appendix C. The engineering formula was evaluated to obtain various CLT design parameters by plugging in the NDS handbook's design value. The observed design values of hybrid CLTs and hardwood only CLTs are presented in Appendix D. The green color value represents the observed design value for hybrid CLTs or hardwood CLTs that exceeded the maximum design value reported in PRG 320. The red color value indicates that the CLT layer for a given combination has a lower design value than the minimum reported in PRG 320. The results indicated that CLTs with white oak in the perpendicular layer had higher shear resistance but had lower bending stiffness and shear rigidity. All other lumber types had similar design values, as presented in the PRG 320 handbook except YP only CLTs. Yellow poplar only CLTs had lower bending stiffness compared to the minimum value published in the PRG 320 handbook.

Factor 4: Lumber value

The fourth factor considered was the lumber value of the various species. The lumber value of 2-common grades for each species discussed in Factor 1 was collected and compared at the study design period. The primary reason to choose 2 common grades for a value reference was the presumption that most of the 2 common lumber would make Number 1 and Number 2 structural grade lumber. Number 1 and Number 2 structural grade was the standard grade of lumber used in CLT manufacturing. The value of 2 common green lumber at the planning phase of the log yield study for the various hardwood species is presented in Table 5-2. Based on all four factors considered, yellow poplar was chosen for the log yield study. Yellow poplar has the lowest specific gravity (SG) of 0.43, within the range of SG of softwood lumber currently recognized by PRG 320. The YP's strength properties are within the range of the softwood lumber types recognized in PRG 320. Although the YP only CLT's flatwise bending value was lower than the published PRG 320 design value, the experimental data obtained by Mohadmadhaz et al. (2015) and Beagley et al. (2014) was higher than this calculated value. The YP production volume percentage is approximately 15% of the total hardwood lumber production in the US. YP's green lumber value was also substantially lower than other species considered for the log yield study, excluding beech. Although beech has a lower lumber value, it has higher SG, and there was not enough of the lumber sawn in modern sawmills.

5.1.6.2 Log yield study procedure for a pilot study.

The overall method adopted for the pilot study is shown in Figure 5-2

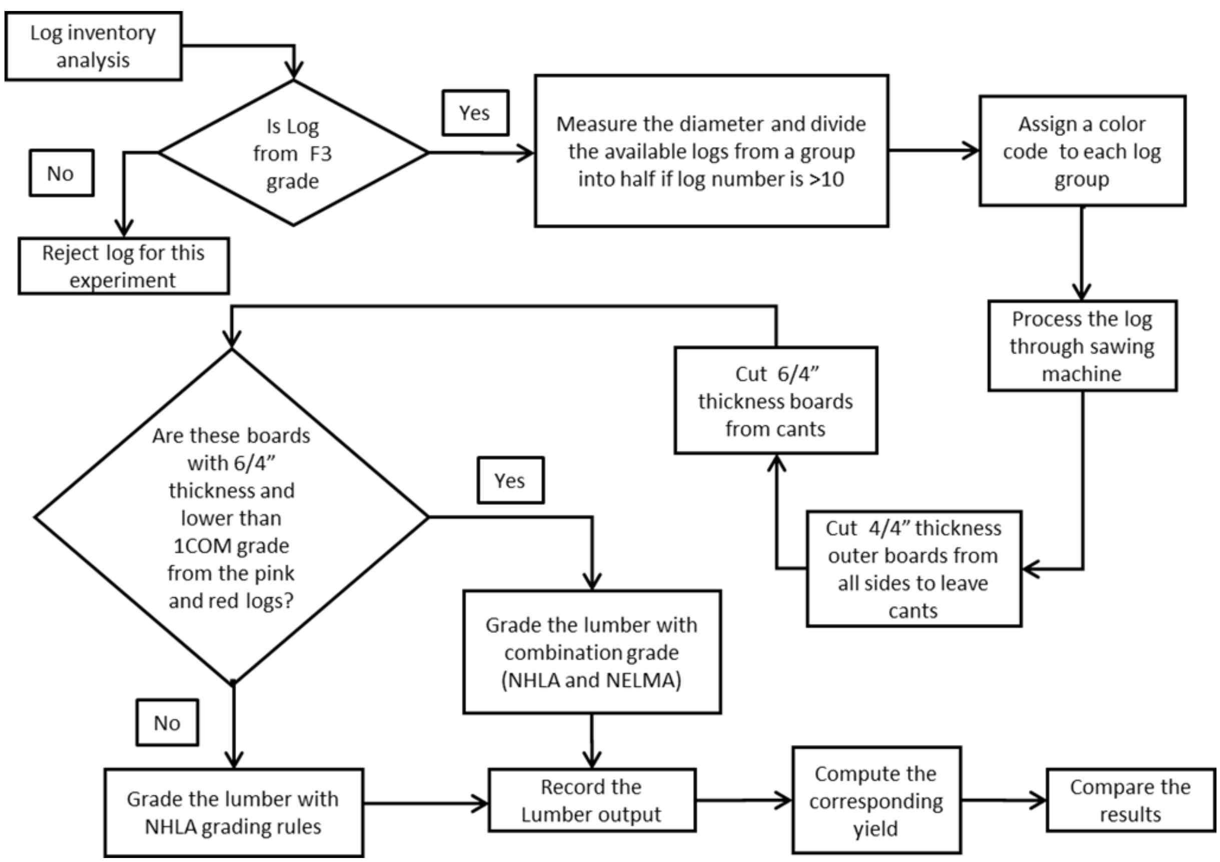

Figure 5-2: Adopted procedure to complete the pilot log yield study.

5.1.6.3 Material for the pilot study.

There was a wide range of logs available on the market. With limited resources, it was not possible to consider each log grade group. Thus, the most representative log dimension, representing the highest volume in the YP inventory, was selected based on the published database. There were two published log yield databases for YP, one by Hank et al. (1980) and another by Grushecky et al. (2008). Hank et al. (1980) reported a yield of 1545 YP logs, and Grushecky et al. (2008) reported a yield of 599 YP logs. From these databases, it was observed that logs with diameters between 10 to 20 inches and 12 feet long were dominant in both studies. Due to limitations of the resources and to observe the log yield based on log length, diameter, and grade, logs with 12-feet lengths and small end diameters, between 12 to 15 inches, with US Forest Service (USFS) F2 and F3 grade, were selected as the material.

The participating sawmill collected logs for this study. Only 39 yellow poplar logs were available in the inventory of the sawmill with the required specifications. The sawmill was unable to collect 15" diameter logs. Only five logs were available with 14" diameters at the study time. All available logs were sorted by diameter to produce five log groups. Logs were first color-coded as white, orange, blue, red, and pink by diameter and log types as control and test samples to track the logs and lumber while in process.

5.1.6.4 Lumber Sawing and Grading Method

The new sawing method's objective was to continue producing higher-grade lumber from the logs' outer zone and produce SGHL from the logs' center. Allison et al. (1987) developed a method to saw mixed grade lumber from YP logs, and the same method was adopted with one change in sawing the logs. Allison et al. (1987) proposed sawing heart center cants first and resawing the SGHL from the cants. The outer boards in each log were cut to 4/4" thickness and continued to get more 4/4" thickness lumber if the log had the potential to yield higher-grade lumber. Cants were left to saw 8" or 6" width SGHL, and cants produced for this experiment did not require being heart-centered and could be obtained from any part of the logs. Cants were then sawn to obtain boards of 6/4" thickness, as shown in Figure 5-3. CLT mills prefer 2" x 6" and 2" x 8”-dimension lumber in their production line, so 6" and 8" width lumber were produced from the cants. The chosen dimensions of lumber were verified with the results from the CLT mill survey from Chapter 3. The lumber thickness was chosen as 6/4" to maintain similar lumber dimensions as softwood lumber used in the CLT.

The participating sawmill produced both hardwood and softwood lumber; thus, the operator was asked to saw the cants as though they were softwood cants to get 6/4" lumber. Sample boards produced from the orange and blue colored logs were defined as the control samples for 12 and 13-inch diameter logs. Control samples were graded using only NHLA grading rules (appearance grade). Boards produced from red, pink, and white-colored logs were the test logs for 12, 13, and 14-inch diameters. Test samples were graded using a two-grading method. First, all lumber was graded with NHLA grades, and later mixed grade (NHLA and NELMA) rules were applied. All lumber graded as NHLA 2 common and below and 6/4" thick pallet grade lumber was graded with NELMA grades separately. Grading 2 common and 6/4" inch thick lumber with both NHLA and NELMA grades separately helped utilize 14" diameter logs for the pilot study. There were only five 14" logs, which was not sufficient to use for control and test samples. Thus, all logs were grouped as test samples. All 2 common and lower 6/4" thick pallet grade lumber was graded with both NHLA and NELMA grades separately to evaluate the yield.

Two graders were used for this experiment—grader one graded under NELMA and NHLA rules while grader two graded under NHLA rules. All the grading was completed after the lumber came out from the green chain sorter. Thus, the minimum requirements to apply structural grades were compromised. NELMA grades cannot be applied unless the lumber to be graded in its final use state. The lumber should be prepared to the required moisture content, surfaced, ripped, and trimmed before grading. Modification to the lumber's physical condition should be examined again before use (NELMA, 2019). All the grade outcomes from this experiment were estimated based on freshly sawn lumber appearance, allowing the required trimming and ripping.

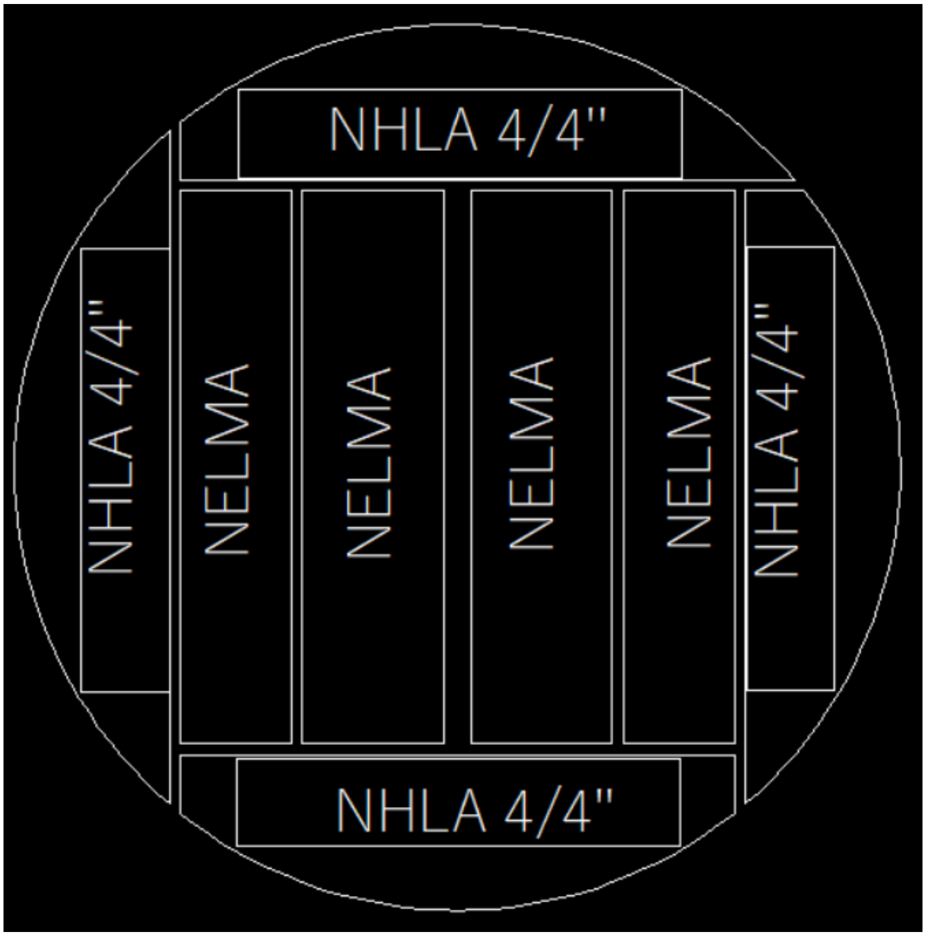

Figure 5-3: Generalized log sawing procedure for the experiments

All lumber produced was graded according to the sawmill's existing practices. This sawmill did not grade the lumber below 2 common with NHLA grades and it was separated for pallet use. The participating sawmill provided the lumber value of both NHLA and NELMA grade lumber for economic calculation. The lumber value used for the revenue analysis based on various lumber grades for this study is shown in Table 5-3. For 12" and 13" diameter logs, revenue was compared as control (NHLA grade only), test-NHLA (NHLA grade only), and test-mixed (NELMA grade to only 6/4" thick lumber).

Table 5-3: Lumber types and corresponding unit values for revenue calculation; Source: participating sawmill

Lumber Grade	*FAS*	*1 common*	*2COM*	*Pallet*	*#1*	*#2*	*#3*
Lumber value per bf	1.04	0.72	0.51	0.34	0.4	0.35	0.3

The observed log yield from the pilot study is presented in Appendix E, Table 9-5, and Table 9-6. Higher revenue was observed when all 6/4" thick 2 common and below lumber was graded with NELMA rules for test samples and compared to the same lumber's revenue using NHLA grades. However, differences in revenue cannot be verified statistically because log yield was recorded as the average of all logs by the color group and corrected for full-scale study. The revenue comparison of the logs is presented in Appendix F, Figure 9-1. Compared to control samples, 12" diameter logs had reduced revenue, but 13" diameter logs showed increased revenue.

Improved revenue from mixed grading lumber production was observed when only NHLA grade pallet lumber with thicknesses of 6/4" and widths of 6" and 8" were graded using NELMA rules. The recovery chart is shown in Appendix F, *Figure 9-2*. The higher revenue per log from the control sample is due to the higher FAS lumber volume recovered for 12" diameter logs. The sample size for this experiment was minimal, and these sample logs were mixed log grades of F2 and F3. Mixed log grades added higher variation to a small sample size experiment, so it was hard to make a general conclusion for all log diameters. However, this experiment concluded that there was more revenue from all log grades when only pallet graded lumber from NHLA was graded with NELMA rules. In conclusion, this experiment validates that mixed grade lumber production may convert lower-grade lumber to structural grade lumber at a higher value.

The pilot study helped show that hardwood sawmills could generate more revenue if they adopted new sawing procedures to manufacture SGHL from YP logs but lacked statistical analysis to measure the significance of the differences. Sawmills may recover more revenue when 6/4" pallet grade lumber was re-graded with NELMA grade lumber compared to grading all 2 common and below-grade lumber. The results for 12" diameter log also suggest that SGHL from higher grade logs may not be economically feasible. Higher-grade lumber had higher revenue differences with NELMA graded lumber, so mixed lumber production reduced the yield. This pilot study helped illustrate the following limitations of the study:

1. Mixed log grades for the same diameter groups added higher variation in lumber outcomes and made it harder to compare yields.
2. Thirty-nine logs were sawn, and only nine, seven, and five logs were sawn as test samples for 12’’, 13’’, and 14’’ diameter logs. The sample size needs to be increased to ensure each log adds minimum variation in yield results.
3. Due to a mix of both F2 and F3 grade logs, higher-grade lumber yield does not reflect the lower grade lumber's revenue when graded for structural application.

The pilot study was helpful in many ways for developing a full-scale log yield study by eliminating the factors that negatively impact decision making. With many limitations, revenue from the pilot study illustrated the feasibility of the process. It helped to develop a full-scale study protocol. Thus, for the full-scale log yield study, the following parameters were set to obtain more precise results:

1. The grade of all logs under study should be the same, so USFS- F3 grade was chosen for the full-scale study.
2. As wood has high variation, the full-scale study's sample size should be increased to the maximum. A minimum of 15 logs per grade group was chosen to allow at least a 10% input variation from each log.
3. Lumber yield from each log from the test and control samples for each diameter were recorded separately. Such practice helps to identify the variation in yields and their impact on revenue.
4. Comparing the yield of NHLA grade and mixed grade from the same lumber was not helpful because NHLA grade lumber and SGHL are produced with different procedures. Lumber volume revenue for NHLA grade was increased because of the minimum saw kerf line and lower allowance loss due to the reduced amount of lumber for SGHL production. Additionally, lumber thickness for SGHL is not a common thickness choice for sawing hardwood lumber, so it is hard to market SGHL as NHLA grade lumber. Thus, only the yield between the control sample (using NHLA grades) and test samples (mix graded with NHLA and NELMA) was chosen to compare the revenue.

5.1.7 **Method for Full-Scale Log Yield Study**

5.1.7.1 Log selection and sorting

The overall method adopted is shown in Figure 5-4. Grade group selection, log sorting, and grading methods were like the pilot study. One hundred twenty-six logs with diameters from 12" to 15" and a length of 12 feet of USFS F3 grade were collected to ensure that there were at least 30 logs for each grade group. Fifteen logs for each grade group were randomly selected as control samples to saw as per the sawmill's existing practice. Another 15 logs for diameter 12’’ and 15’’ and 18 logs for diameter 13’’ and 14’’ were selected and sorted as test samples to saw with the proposed new sawing method to produce mixed grade lumber. Each log from the control and test samples of all four-grade groups was processed as a single batch, except for the last three batches, which included one log each from 13" and 14" diameter logs.

5.1.7.2 Sawing method and lumber grading

The cant sawing method was adopted to break logs into lumber. Logs were first sawn to rip each side, without cutting jacket boards, to obtain the largest possible cants in the head break. Lumber was sawn on the resawing machine. Logs in control samples were sawn using the existing sawing practice of the sawmill. Each log was first sawn to leave cants, and cants were gang sawn to obtain 4/4" thick lumber. Each log was first sawn to cut 4/4" thickness outer boards leaving cants to saw 6" or 8" wide lumber for test samples. Most of the time, logs with 12" and 13" diameters were sawn to obtain 6" wide lumber, and logs with 14" and 15" diameters were sawn to obtain 8" wide lumber. Six-inch and 8" width lumber was used, as these are the standard lumber widths used by CLT manufacturers. Both lumber outputs were recorded as bf of lumber. Lumber obtained from a single batch was first collected, sorted, bundled, and removed from the production line before another batch was processed to avoid mixing.

All control and test lumber were separately graded using both NHLA and NELMA grading rules. The thickness of the lumber produced from this yield study was 4/4" and 8/4", which is the acceptable thickness of lumber used in CLTs. Thus, all lumber was graded with NELMA grades and NHLA grades, and results were used to develop the grade relation between both grading rules. To determine the revenue for different scenarios, appropriate lumber grade and corresponding bf of lumber were used.

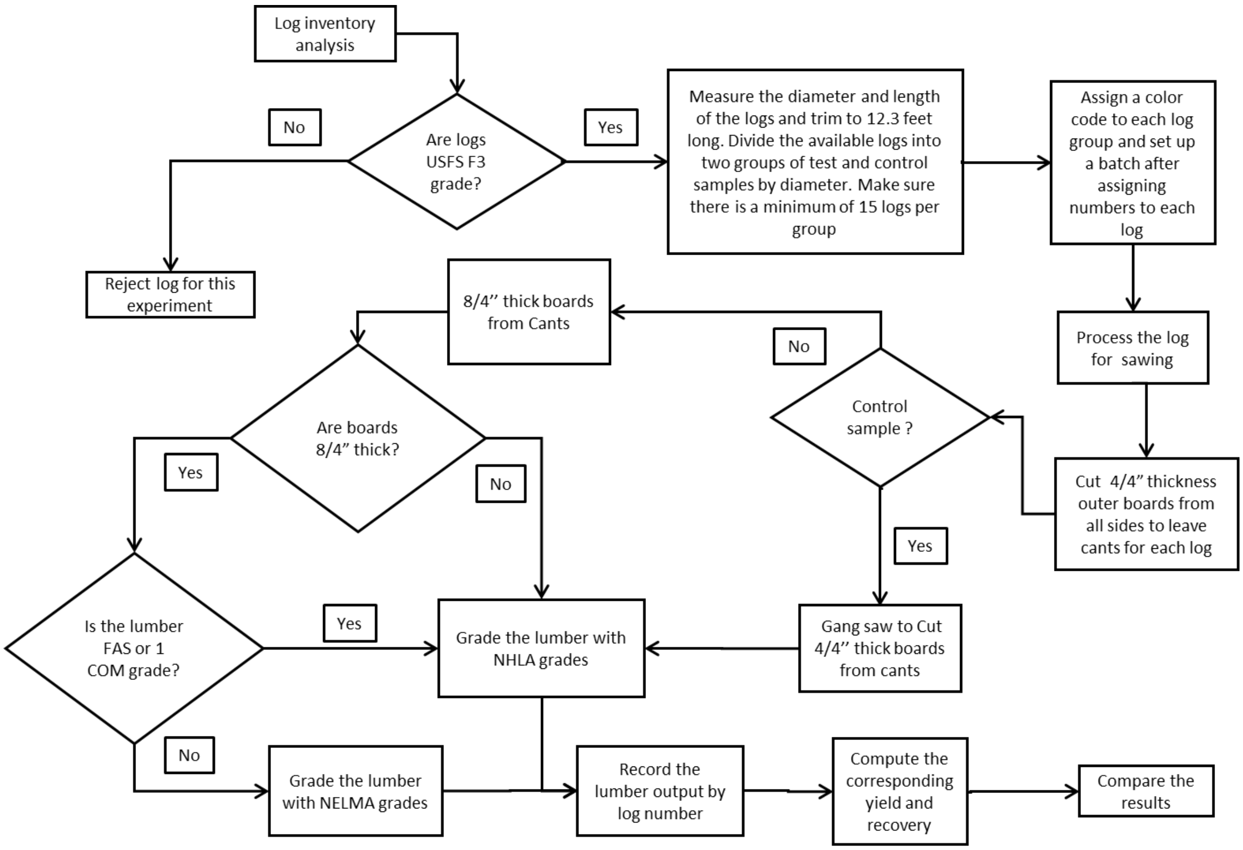

Figure 5-4: Adopted procedure to complete the full-scale log yield study

5.1.7.3 Lumber outcomes recording

Three different spreadsheets were designed to record the lumber outputs. NHLA graded lumber outputs were recorded under FAS, 1 common (1 COM), 2A common (2A COM), 2B common (2B COM), 3A common (3A COM), 3B common (3B COM), and Below Grade (BG). The Second spreadsheet was designed to record only NELMA graded lumber for all lumber types. The third spreadsheet was designed to record mixed grading (NHLA+ NELMA) of lumber. Mixed graded was assigned under FAS, 1 common, 2A common, 2B common, 3A common, 3B common, BG, Structural Selects (S. Selects), Number 1(NO 1), Number 2 (NO 2), Number 3 (NO 3), and Economy grade (ECO). All 4/4" lumber was NHLA graded and recorded, and for 8/4," lumber NELMA grades for the lumber were recorded. Lumber outcomes were sorted to observe the total board feet of the lumber from each log grade group.

5.1.8 Economics of Yield Analysis

The log yield analysis economics were completed with the referenced price for both NHLA and NELMA grade lumber. The NHLA grade lumber reference value was derived based on the Hardwood Market Report (HMR) for June of 2020 and the participating sawmills' information. The reference value for the NELMA grade lumber was obtained in three steps. First, the average production cost of the NHLA grade lumber by grade was evaluated. In the second step, the relation between NHLA grade and NELMA grade was established based on yield data from a full-scale log yield study. Finally, steps one and two were used to obtain SGHL lumber value after adding surfacing and grading. Each step is discussed in the following paragraphs.

5.1.8.1 Evaluating production cost of NHLA grade lumber

The production cost for NHLA grade lumber were evaluated by using the market-based tool method. First, the average lumber production cost was evaluated using the pricing strategies suggested by Hansen (2011) for the market-based tool method. Hansen (2011) & Gisele et al. (2015) suggested that the market-based tool method is more appropriate for mass production of low value products in the forest sector. The market-based tool can be applied if:

1. Mass production is appropriate for the product.
2. Product value depends on supply and demand.
3. The product is like other commodity products

The market-based tool method was appropriate to price the NHLA grade lumber because NHLA grade lumber is produced as a mass product, and demand and supply of the lumber control the value. Lumber is a commodity product; thus, there are very few specialized variations.

According to Gisele et al. (2015), a market-based tool method should be used when considering the two major factors. The first factor is to use the value from a leading company in the market, and the second is to use a reference from a pricing newsletter. The participating sawmill for the log yield study was the leading company since it could produce more than 50 MMBF per year from various plants across the US. Thus, the lumber value of that company was the first reference price. The average production cost from January 2020 to June 2020 was determined based on the YP lumber production percentage during the same period. The second reference price was from the Hardwood Market Report from the same period to get the lumber's average value by grade. The average cost of producing 1000 bf of lumber of all lumber grades from yellow poplar was evaluated first. Thus, production cost was proportionally distributed to all lumber grades based on various cost factors.

5.1.8.2 Developing a comparable relation between NHLA and NELMA grade lumber

All the yellow poplar lumber produced from the log yield study was graded using both NHLA and NELMA grades. The idea of grading lumber using two different grading rules was to establish a relation between grading methods. Using the outcome, a company could choose to process SGHL based on potential yield value. Both NELMA and NHLA are visual grading rules, but there are differences in the grading criteria. There are different measures to accept or reject defects on the lumber surface for both grading rules. Some of the higher NHLA grade lumber can grade lower NELMA grade lumber and vice-versa. Thus, all the NELMA grade lumber was evaluated for yield percentage based on the corresponding NHLA grade.

5.1.8.3 Estimating the cost of SGHL from YP

None of the sawmills in the US are currently producing SGHL for structural applications. Therefore, it was difficult to estimate the production cost of SGHL. The production cost of NHLA grade lumber from the log yield study from Section 5.1.8.1 and the NELMA grade lumber yield data of grade comparison from Section 5.1.8. 2 was utilized to find the production cost of the SGHL from YP. First, all the lumber was grouped under NHLA grade, and the corresponding bf by grade was summarized. A NELMA grade vs. NHLA grade table was developed from the data. NHLA grade lumber production cost per bf by grade was used to determine the cost of producing each bf of lumber by NELMA grade.

An additional three processes —drying, surfacing, and applying NELMA grade— are required to prepare SGHL from lumber produced as NHLA grade lumber. All the lumber produced for this experiment was assumed to be dried below 15% moisture content, so the cost of drying was included with the assigned NHLA grade lumber value. The participating sawmill provided the cost to surface all four lumber sides, assuming the lumber was surfaced as part of the continuous lumber production process and cost $20 for surfacing per MMBF. NELMA was contacted to find out the cost of grading SGHL. NELMA does not provide grading certification to the sawmills in West Virginia and Virginia, where the log yield study's participating sawmills were located. However, NELMA has on-demand service for noncertified sawmills and can provide similar services four times a year. The NELMA grader who helped in the log yield study suggested grading up to 30,000 bf of lumber per shift. NELMA was paid $500 per day for this service. Additionally, the sawmill had to cover the cost of transportation and the grader's daily expenses, and another $500 per day was assumed to cover all other expenses. The estimated average cost per day was $1000. This estimation assumed that the grader could grade 20,000 bf of lumber per day to cost $20 per 1000 bf of lumber production. Thus, the estimated average production cost for NHLA grade lumber was used to determine the cost of the SGHL by assigning an additional $40 per MMBF.

On top of the production cost, a 15% profit was added to obtain the lumber value of the SGHL. A 15% profit margin was selected based on the expected average return from the NHLA grade lumber. There was no information on the market value of different SGHL grade lumber, so it was impossible to assign a different profit margin by lumber grade.

All lumber sawn was evaluated at the estimated value for both NHLA and NELMA groups and compared to revenue differences. For revenue analysis, two different methods of lumber production were assumed. The first method was to grade all SGHL lumber graded as NHLA 2 common and lower with NELMA grade with economy grade and called an MGAL1 method. The second method was to exclude economy grade for NELMA grading from the MGAL1 method and called an MGEE method. The observed revenue from both methods was compared using two-way ANOVA.

5.2 Observations and Results

There were 18 batches of logs sawn to complete the log yield study, and each batch contained one log from both test and control samples from each diameter group for the first 15 batches. Each batch of lumber was bundled together and included lumber from four control and four test logs separated by color and had a log number on the face. The last three batches consisted of one log of 13" and 14" diameter each and were sawn as test samples. All the logs were sawn in the second week of December 2019 and graded after six months as rough green lumber. Grading was initially scheduled in March, but due to the global pandemic, it was rescheduled for the second week of June. As all lumber was graded rough and green without required trimming, ripping, drying, and dressing, it did not meet the minimum requirements to apply structural grades. NELMA was subcontracted to grade the SGHL, and the NELMA grade was applied only for study purposes. NELMA grades cannot be applied unless the lumber is graded in its final state after the required drying, trimming, ripping, and dressing.

The lumber produced for this experiment was not for CLT mills. The participating sawmill had to sell it as NHLA graded lumber. The grader assigned the NELMA grade, estimating the required trimming, ripping, and dressing, assuming the current lumber appearance was the final lumber ready for use in a structural application. Some of the lumber had stains due to fungus. The grader downgraded that lumber, so the lumber's final grade may differ from that recorded for the yield. Lumber exposed to direct sun also developed twisting, warping, and splitting. That lumber was graded according to current lumber conditions. The appearance of the lumber at the time of grading was the basis of assigning a lumber grade. The observed result was interpreted as a lumber grade of rough and green lumber. The recorded lumber grade was the final grade of the lumber used in the economic analysis. Thus, this study did not consider the lumber's potential grade changes after the work that is required to prepare it as ready to use lumber. The yield of each log by diameter and log types as control or test sample is presented in Appendix G.

5.2.1 Lumber Grade and Observed Yield

One hundred twenty-six logs were sawn, and 1317 lumber pieces were obtained for this experiment. The measured lumber volume from the experiment was 12008 bf when all the lumber was graded using NHLA grading rules. This observed lumber yield was recorded after rounding to the nearest whole number for each lumber piece using the standard mathematical method of rounding to the nearest whole number, and if the number observed was 0.5, the lower value was recorded. Under NHLA grading, 70% of the lumber graded as 2 common, and less than 15% of the lumber graded as 1 common and better. Only 14% of the lumber was graded as 3 common, and the volume of the below-grade lumber was less than 2%. The distribution of the lumber by grade and corresponding bf is presented in Table 5-4.

Table 5-4: Observed lumber yield from the experiment when all logs were graded with NHLA rules.

Lumber Grade	*Lumber Count*	*Measured bf*	*Yield percentage*
FAS	37	327	2.81%
1 common	153	1410	11.62%
2A common	201	1861	15.26%
2B common	716	6511	54.37%
3A common	42	319	3.19%
3B common	152	1429	11.54%
BG	16	151	1.21%
Total	1317	12008	100.00%

There were 1002 lumber pieces sawn as a 4/4" thick that measured 7353 bf of the lumber under the NHLA grading rule. More than 70% of lumber was graded as 2 common whereas 14 % of the lumber was graded as 3 common from the 4/4" thick lumber. The volume of 1 common and better lumber was less than 15%. The observed lumber grade outcomes by lumber thickness are presented in Table 5-5 and Table 5-6.

Table 5-5: Lumber outcomes by grade and bf for 4/4" thick lumber sawn from all logs under NHLA grade.

Lumber grade	*Lumber count*	*Measured bf*	*yield percentage*
FAS	29	207	2.89%
1 common	112	829	11.18%
2A common	148	1089	14.77%
2B common	554	4096	55.29%
3A common	38	267	3.79%
3B common	111	803	11.08%
BG	10	62	1.00%
Total	1002	7353	100.00%

From all 4655 bf of 8/4" thickness lumber, more than 17% was graded as 1 common and better. More than 68% of the lumber was graded as 2 common, and less than 15% was graded as 3 common and lower.

Table 5-6: Lumber outcomes by grade and bf for 8/4" thick lumber under NHLA grade.

Lumber Grade	*Lumber count*	*Measured bf*	*Yield Percentage*
FAS	8	120	2.54%
1 common	41	581	13.02%
2A common	53	772	16.83%
2B common	162	2415	51.43%
3A common	4	52	1.27%
3B common	41	626	13.02%
BG	6	89	1.90%
Total	315	4655	100.00%

There were 4485 bf of 8/4" thick lumber sawn for this experiment and graded as NELMA grade lumber. The observed yields were 73% of Number 2 and better grade lumber. Twenty percent of the lumber was graded as structural selects, and 17% was graded as Number 1 grade lumber. Also, 24% was graded as Number 3 grade, and less than 4% was graded as an economy grade lumber. The details of the NELMA graded lumber are presented in Table 5-7.

Table 5-7: Lumber outcome by grade and bf for 8/4" thick lumber when graded with NELMA grading rules.

Lumber Grade	*lumber Count*	*Measured bf*	*Yield Percentage*
S. SELECTS	62	881	19.64%

Number 1	54	765	17.06%
Number 2	111	1612	35.94%
Number 3	76	1047	23.34%
economy	12	180	4.01%
Total	315	4485	100.00%

5.2.2 Lumber Yield by Lumber Length

The lumber value for NELMA graded lumber varies with the lumber length. Thus, to find the actual return, each piece should be evaluated based on its length. In general, the value difference is not significant per bf. However, when dealing with a larger volume, it can be a significant factor. The lumber distribution by lumber length for all 8/4" thickness lumber graded under NELMA graded lumber is presented in Table 5-8.

Table 5-8: Distribution of lumber yield by lumber length graded under both NHLA and NELMA.

Lumber length (feet)	*Lumber Count*	*Measured bf*	*Yield Percentage*
4	1	5	0.12%
6	7	34	0.81%
7	2	9	0.21%
8	8	76	1.80%
9	8	80	1.89%
10	24	239	5.66%
11	8	103	2.44%
12	257	3676	87.07%
Total	315	4222	100.00%

5.2.3 Lumber Yield by Log Diameter

Each log was evaluated individually for both control and test samples. All lumber from control samples was graded with NHLA grading rules. All 4/4" thick lumber from the test samples was graded with NHLA rules, and the remaining 8/4" thick lumber was graded with NELMA grading rules. More than 65% of the lumber's total volume was graded as 2 commons for each control samples' diameter group. The observed lumber outcome by log diameter for the control and test samples with NHLA and NELMA lumber grades are summarized in Table 5-9 and Table 5-10. The average lumber yield was higher for test samples compared to the control samples. The details of the comparison are presented in Table 5-11 and Figure 5-5.

Table 5-9: Summary of total lumber outcomes from the control samples, graded using NHLA rules by log diameter.

Dia	*N*	*FAS*	*1 com*	*2 A com*	*2B com*	*3A com*	*3B com*	*BG*	*Average bf*
12	15	0%	5%	17%	61%	4%	13%	0%	68
13	15	4%	9%	12%	60%	9%	5%	0%	77
14	15	2%	12%	24%	54%	2%	7%	0%	89
15	15	4%	17%	12%	56%	2%	8%	0%	99

Table 5-10: Summary of total lumber outcomes from the test samples with mixed lumber grades (NHLA +NELMA) rules by log diameter.

Dia	*N*	*FAS*	*1 common*	*2 A common*	*2B common*	*3A common*	*3B common*	*BG*
12	15	2%	2%	4%	20%	2%	5%	1%
13	18	1%	2%	6%	14%	0%	7%	1%
14	18	2%	7%	2%	16%	1%	5%	2%
15	15	1%	5%	6%	20%	0%	4%	0%
		SS	NO1	NO2	NO3	Economy	Average bf/log	
12	15	17%	9%	22%	16%	1%	75	
13	18	6%	18%	30%	13%	1%	84	
14	18	14%	8%	18%	21%	6%	111	
15	15	16%	11%	25%	11%	2%	132	

There were 14%, 18%, 32%, and 39% higher yields for logs with 12, 13,14, and 15-inch diameters, respectively. For 12" diameter logs, the observed mean for the control sample was 68 bf, and the test sample yielded an average of 75 bf (p= 0.0280) per log. For 13" diameter logs, the control samples had an average yield of 77 bf. However, the test samples yielded an average of 84 bf (p= 0.0077) per log. The observed average log yield for control samples for 14 and 15 inch logs was 89 bf and 98 bf, and for test samples, the average yield was 111 bf (p = <0.0001) and 132 bf (p = <0.0001), respectively. The p-value for each diameter group is observed from a two-way ANOVA test.

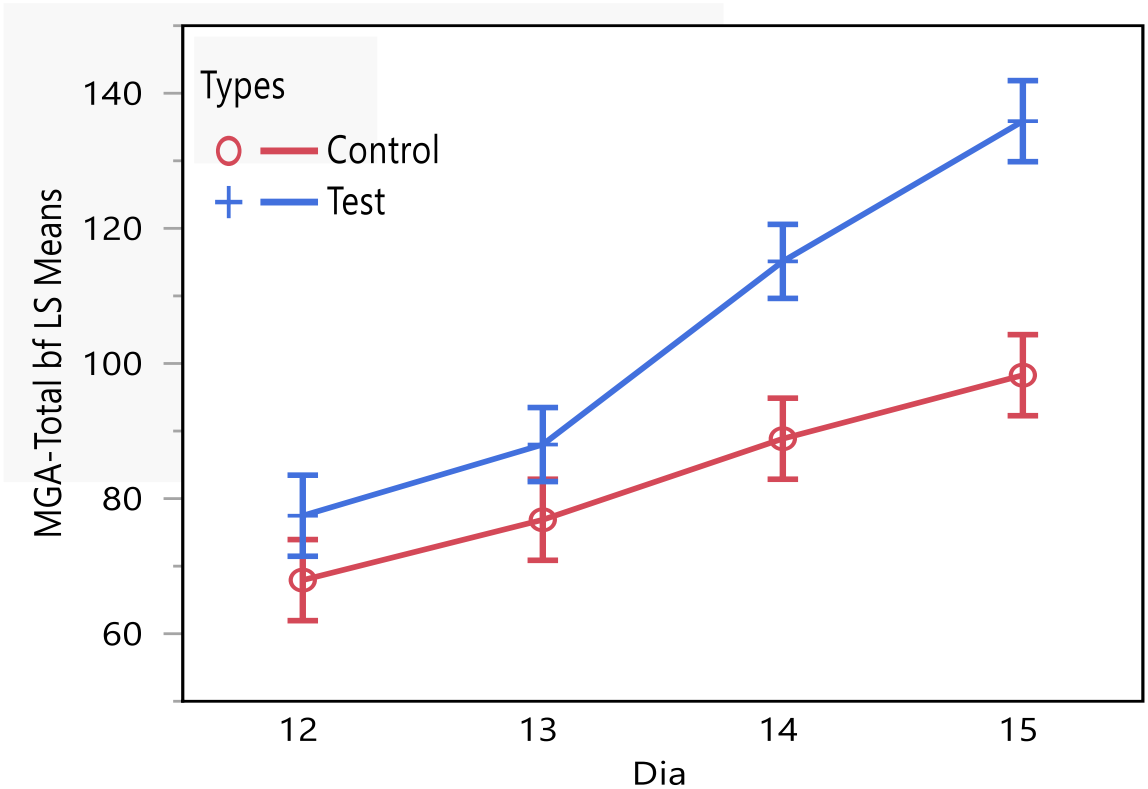

Figure 5-5:Least squares mean plot of log yield by diameters and types.

Production of SGHL substantially reduced the volume of lower grade lumber for each diameter group. For 12" and 13" diameter logs, the percentage of lower grade lumber produced was more than 85% compared to the control sample. SGHL production from cants reduced it to below 32% and 28%, respectively, in test samples. The lower grade lumber volume from mixed grade lumber production shrank to below 25% and 30% from more than 85% and 78%, respectively, for 14" and 15" diameter logs from the control sample.

Table 5-11: Yield comparison from control and test samples when all 8/4" thick lumber from test samples were graded with NELMA rules.

	Control			*Test*				
Diameter	N	Average bf	SD bf	N	Average bf/log	SD bf	Average Yield Difference	p-value (Two-way ANOVA)
12	15	68	6	15	75	9	7	0.0280

13	15	77	9	18	84	14	7	0.0077
14	15	89	10	18	111	14	22	<0.0001
15	15	99	13	15	132	14	33	<0.0001

The details of the SGHL yield from all test samples by the diameter group are presented in Table 5-12. For the test samples, approximately 67% of the lumber was sawn to structural grade for each diameter group. For 12" diameter logs, 34% of the lumber was sawn as 4/4" thick lumber. For 13" diameter and 14" diameter logs, almost 70% and 68% of the lumber were sawn as 8/4" thick lumber. Close to 66% of the lumber yield was of 8/4" thick lumber for 15" diameter logs.

Table 5-12: Volume distribution of the log yield from test samples based on lumber thickness and diameter

Log Diameter	*4/4" thick lumber %*	*8/4" thick lumber %*	*Average bf*
12	33.63%	66.37%	78
13	29.68%	70.32%	91
14	32.20%	67.80%	118
15	34.06%	65.94%	138
Average	32.40%	67.60%	-

The average yield of structural grade lumber from the cants of the 12, 13, 14, and 15-inch diameter logs were 50, 61, 75, and 86 bf, respectively, from this experiment as presented in Table 5-13. For diameter 12,14, and 15-inch logs, select structural grade lumber was more than 20%, but 13" diameter logs yielded only 8% as select structural. The Number 1 and better lumber volume was over 30 % for each log diameter.

Table 5-13: Structural grade lumber yield by log diameter from test samples

DIA	*N*	*SS*	*NO1*	*NO2*	*NO3*	*economy*	*AVERAGE bf*
12	15	25.9%	14.2%	34.4%	23.8%	1.6%	50
13	18	8.1%	25.6%	44.2%	19.9%	2.2%	61
14	18	21.2%	12.0%	26.6%	31.6%	8.6%	75
15	15	24.2%	16.7%	39.6%	17.3%	2.2%	86
Average		19.6%	17.1%	35.9%	23.3%	4.0%	

For 12, 13, and 15-inch diameter logs, the volume percentage of Number 2 and better logs was over 75%. For 14" diameter logs, it was only 60%. In total, 20% of the lumber was graded as select structural, and more than 72% was graded as Number 2 and better.

5.2.4 **Economics of a Log Yield Study**

5.2.4.1 The production cost of the NHLA grade lumber

As discussed in the methodology, the average production cost for 1000 bf of the lumber from all yellow poplar lumber grades was determined based on YP lumber's total volume produced from January to June. The total volume of YP lumber produced from the mill was summarized as the lumber's yield percentage by grade. The selling value of the lumber by grade for the same period was researched for each lumber grade. Based on the HMR report for the same period and selling value for each lumber grade, the lumber's average selling value for each grade was evaluated. This selling value was referenced to derive production cost by subtracting average profit margin, which was assumed as 15%, as suggested by the company. The observed cost for each lumber grade to the nearest multiple of the five is presented in Table 5-14. The average production cost for 1000 bf of all grade NHLA lumber was evaluated as $495.

Table 5-14: Production cost of the NHLA grade lumber with a percentage share of the various cost factors.

Cost Factor	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*	*Average*
Total	$955	$685	$470	$425	$325	$325	$160	$495

5.2.4.2 NHLA and NELMA grade lumber relation

There were 1317 pieces of lumber from the log yield study. When applying NELMA grades to all NHLA grade lumber, many of the pieces required trimming or ripping. Only the lumber with similar dimensions for both NHLA and NELMA grades was considered to establish a relation between grading rules. Only 436 lumber pieces had similar dimensions for both NHLA and NELMA grades.

Table 5-15: Observed grade yield table for NHLA and NELMA grade lumber.

Lumber Grade	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*
S. Selects	9.00%	20.00%	8.00%	54.00%	1.00%	8.00%	0.00%
NO 1	1.00%	13.00%	14.00%	61.00%	3.00%	8.00%	0.00%
NO 2	1.00%	11.00%	11.00%	59.00%	1.00%	16.00%	1.00%
NO 3	1.00%	10.00%	11.00%	54.00%	3.00%	21.00%	0.00%
ECO	0.00%	5.00%	5.00%	42.00%	5.00%	32.00%	11.00%

Table 5-16: NHLA to NELMA grade conversion equation for YP lumber

NELMA grade	*Conversion equation based on observed data.*
S. selects	0.09 X FAS + 0.2 X 1 COM + 0.08 X 2A COM + 0.54 X 2B COM + 0.01 X 3A COM + 0.08 X 3B COM + 0 X BG
NO 1	0.01 X FAS + 0.13 X 1 COM + 0.14 X 2A COM + 0.61 X 2B COM + 0.03 X 3A COM + 0.08 X 3B COM + 0 X BG
NO 2	0.01 X FAS + 0.11 X 1 COM + 0.11 X 2A COM + 0.59 X 2B COM + 0.01 X 3A COM + 0.16 X 3B COM + 0.01 X BG
NO 3	0.01 X FAS + 0.1 X 1 COM + 0.11 X 2A COM + 0.54 X 2B COM + 0.03 X 3A COM + 0.21 X 3B COM + 0 X BG
ECO	0 X FAS + 0.05 X 1 COM + 0.05 X 2A COM + 0.42 X 2B COM + 0.05 X 3A COM + 0.32 X 3B COM + 0.11 X BG

Out of 436 lumber pieces, 10 lumber pieces were graded as FAS, and 54 pieces were graded as 1 COM. Similarly, 47 pieces, 246 pieces, 10 pieces, and 66 pieces of lumber were graded as 2A COM, 2B COM, 3A COM, and 3B COM, respectively. Only three pieces of the lumber were graded as below-grade. When the same lumber was graded using NELMA grades, out of 436 pieces, 79 pieces and 77 pieces of the lumber were graded as structural select and NO 1 grade, respectively. One hundred forty-seven lumber pieces were graded as NO 2 grade, 114 pieces of lumber were graded as NO 3 grade, and only 19 pieces of the lumber were graded as industrial grade. The NELMA grade lumber distribution by NHLA grade lumber is presented in Table 5-15, and the observed conversion percentage by each grade was used to develop a linear equation and presented in Table 5-16.

5.2.4.3 Cost of SGHL from YP

The NHLA grade lumber's production cost from Table 5-14 and the grade conversion equation from

Table 5-16 was used to calculate the NELMA grade lumber's production cost. The total production cost calculated for NHLA grade lumber was distributed by the percentage of lumber grade yield by NELMA grade. The calculated lumber value for SGHL is presented in Table 5-17. The resulting value per 1000 bf of the lumber for all grade groups used to compare the economics of mix grade lumber production versus the existing production practice of the sawmills is presented in Table 5-18. The estimated lumber value only includes the drying cost for lower NHLA grade lumber.

Table 5-17: Production cost of the NELMA grade lumber based on NHLA grade lumber's production cost and NHLA-NELMA grade conversion equation.

Lumber grade	*Production cost up to drying*	*Production cost with dressing and NELMA grade*	*Lumber cost with 15% profit*
S. Selects	$520.00	$560.00	$645.00
NO 1	$470.00	$510.00	$585.00
NO 2	$440.00	$480.00	$550.00
NO 3	$430.00	$470.00	$540.00
ECO	$380.00	$420.00	$485.00

For the economic analysis of the discussed SGHL production process, lumber that was 4/4" thick and FAS or 1 common grade from the test samples was evaluated as NHLA grade. The remaining 8/4" thick lumber was evaluated with NELMA grades and value. There is a higher value for kiln dried FAS and 1 common lumber compared to structural grade. Thus, to optimize the return, both kiln dried FAS and 1 common from test samples were evaluated as NHLA grade lumber. Additionally, all 3 common and lower grade lumber were evaluated as dried lumber. Thus, the method to produce SGHL was chosen to grade only lower than 1 common NHLA grade lumber produced as SGHL with NELMA and defined as the MGAL1 method hereafter. The observed lumber outcomes for test samples after grading all FAS and 1 common as NHLA grade are presented in Table 5-19.

Table 5-18: Reference value used to calculate the revenue for both NHLA and NELMA grade lumber.

Grading Rules	*Lumber state*	*Lumber Grade*	*Lumber Value ($)*
NHLA Grade	Kiln Dried	FAS	1090.00
		1 common	795.00
		2A common	600.00
		2B common	570.00
	Green/kiln dried	3A common	300.00
		3B common	275.00
		BG	250.00
NELMA Grade	Kiln Dried	S. Selects	645.00
		Number 1	585.00
		Number 2	550.00
		Number 3	540.00
		Economy	485.00

Table 5-19: Summary of lumber outcomes from the test samples when NELMA grades are applied based on MGAL1 method

Dia	*N*	*FAS*	*1 common*	*2 A common*	*2B common*	*3A common*	*3B common*	*BG*
12	15	2%	12%	4%	21%	2%	6%	1%
13	18	1%	10%	5%	15%	0%	9%	2%
14	18	5%	13%	2%	19%	2%	6%	1%
15	15	3%	16%	6%	21%	1%	5%	0%
		SS	NO1	NO2	NO3	Economy	Average bf	SD average bf
12	15	9%	9%	20%	1%	15%	78	9
13	18	3%	15%	26%	2%	13%	88	14
14	18	8%	5%	16%	6%	19%	115	14
15	15	11%	8%	21%	1%	9%	136	14

The average revenue for test samples with log diameters of 12, 14, and 15 inches was higher from the two-way ANOVA test, as presented in Table 5-20 and Figure 5-6. All the assumptions for two-way ANOVA analysis were satisfied by the observed data. One log is spotted as an outlier from the normality test, and the observed higher revenue was attributed to the yield of higher grade NHLA lumber.

Table 5-20: Revenue from control and test samples with MGAL1 method of lumber grading

	Control			*Test*				
Diameter	N	Average	SD	N	Average	SD	Recovery	p-value

		Recovery			Recovery		Difference	(Two-way ANOVA)
12	15	$36.40	$5.35	15	$45.21	$5.44	$8.81	0.0172
13	15	$44.12	$8.69	18	$49.46	$8.56	$5.34	0.1283
14	15	$52.43	$7.25	18	$68.57	$14.86	$16.14	<0.0001
15	15	$59.03	$11.98	15	$82.53	$12.39	$23.50	<0.0001

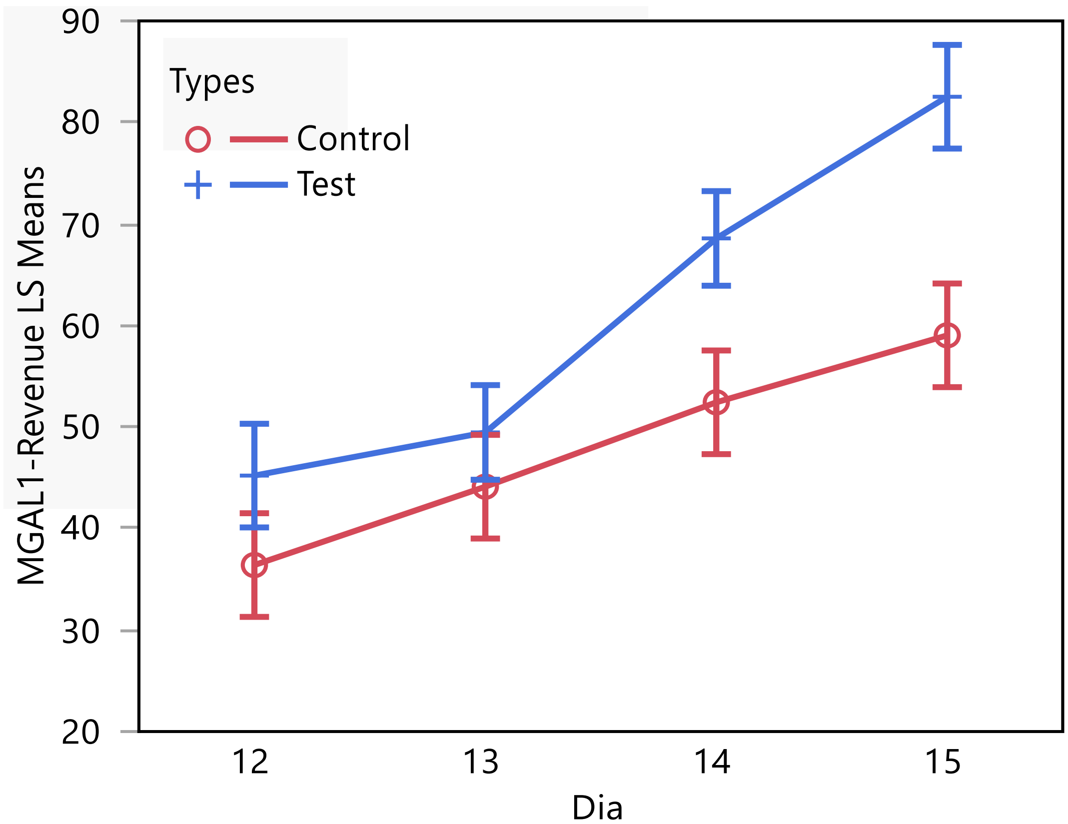

Figure 5-6: Least square means a plot of revenue comparison from test and control samples for MGAL1 method

The observation helps to conclude that there are differences in revenue from test and control samples of logs from all diameter group logs except 13" at referenced lumber value, at α= 0.5. The higher grade NHLA and NELMA grade lumber volume was much lower for 13'' diameter logs from test samples than other log grade groups, so the revenue observed was lower from these experiments.

If a sawmill must produce SGHL for CLT industries, economy grade lumber cannot be used for structural applications. A new lumber production method was defined as the MGEE method, where the economy grade was eliminated for NELMA grading, and NHLA grade was used for lumber yield from MGAL1 methods. The log yield distribution for each diameter group is shown in Table 5-21. As the yield per diameter group changes, revenue from each diameter group also changes. The average revenue for test samples with log diameters of 12, 14, and 15 inches was also higher from the two-way ANOVA test, as presented in

Table 5-22 and Figure 5-7. Diameter 12”, 14", and 15" logs resulted in a statistically significant difference for test samples compared to control samples at α= 0.5. The observed results help conclude that inclusion and exclusion of the economy grade do not impact the log yield outcomes, so if the sawmills are producing SGHL for the CLT market, exclusion of the economy grade SGHL is the best choice.

Table 5-21: Summary of lumber outcomes from the test samples when NELMA grades are applied based on MGEE method

Dia	*N*	*FAS*	*1 common*	*2 A common*	*2B common*	*3A common*	*3B common*	*BG*
12	15	2%	11%	4%	20%	2%	6%	2%
13	18	1%	10%	4%	15%	0%	8%	1%
14	18	5%	12%	3%	21%	1%	6%	2%
15	15	2%	15%	6%	20%	0%	4%	2%
		SS	NO1	NO2	NO3	Average bf	SD average bf	
12	15	9%	9%	21%	15%	78	9	
13	18	3%	17%	27%	12%	88	14	
14	18	8%	6%	16%	19%	116	15	
15	15	12%	7%	21%	9%	137	14	

Table 5-22: Revenue from control and test samples with MGEE method of lumber grading

	Control			*Test*				
Diameter	N	Average Recovery	SD	N	Average Recovery	SD	Recovery Difference	p-value (Two-way ANOVA)
12	15	$36.40	$5.35	15	$45.02	$5.16	$8.62	0.018
13	15	$44.12	$8.69	18	$49.58	$8.66	$5.46	0.1155
14	15	$52.43	$7.25	18	$68.90	$14.42	$16.47	<0.0001
15	15	$59.03	$11.98	15	$82.16	$12.11	$23.13	<0.0001

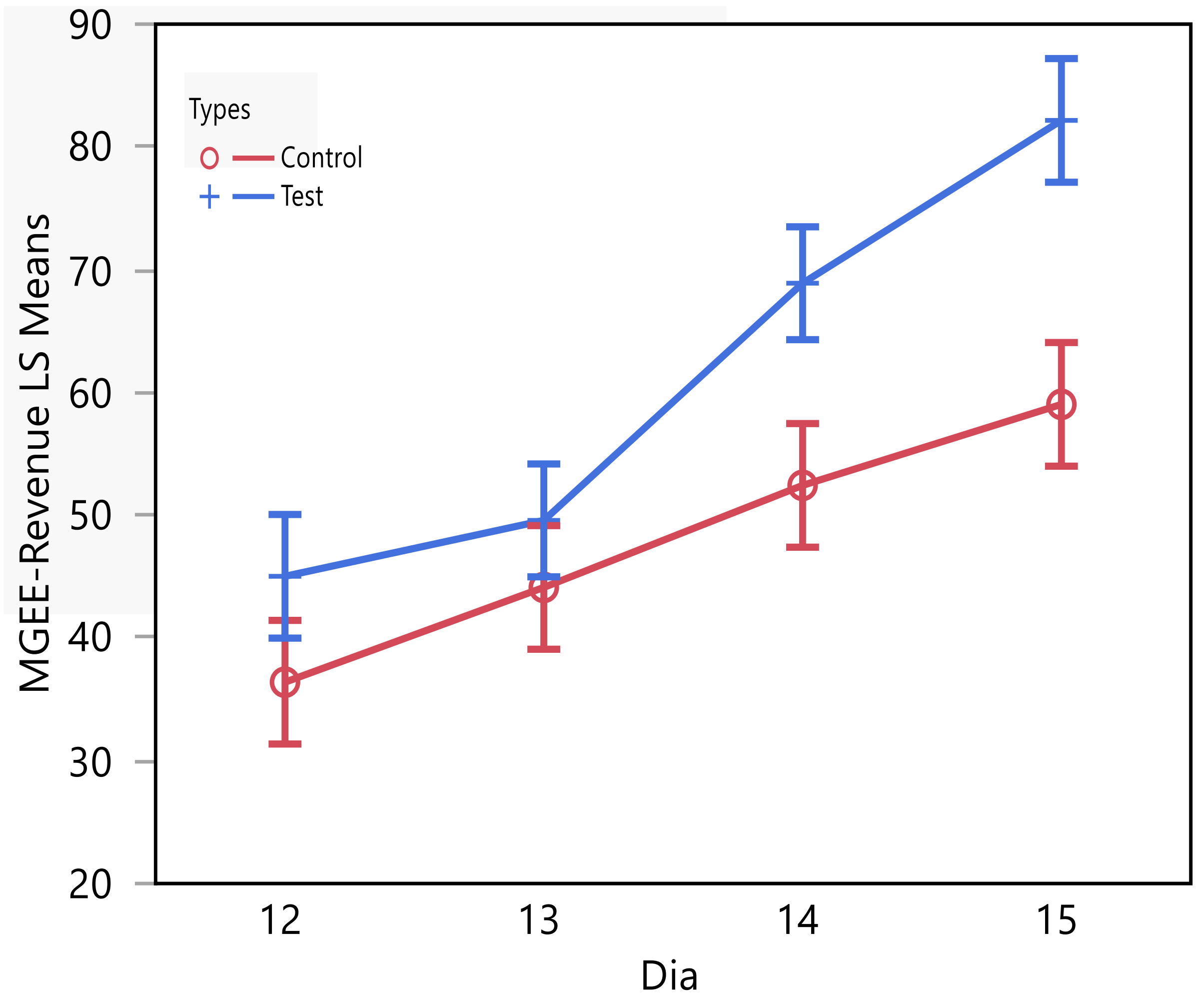

Figure 5-7: Least square means a plot of revenue comparison from test and control samples for MGEE method of lumber production

5.3 Discussion and Conclusions

The full-scale log yield study was completed after addressing the pilot study's limitations to produce CLT grade structural lumber from YP logs. The yield from each log was recorded separately and analyzed for potential revenue. The full-scale yield study resulted in a higher volume of lumber for the test samples than the control samples. One of the higher yield reasons was a lower saw-kerf loss since 8/4" thick lumber was sawn from all samples, which accounted for over 65% of the lumber volume.

This experiment's results are like the results observed by Allison (1987) with higher lumber yields for mixed grade lumber production. Allison (1987) stated the higher yield was due to a minimum sawdust line and a full 8/4"count for the 7/4" green lumber. However, this was not the case in this experiment, as all cants were sawn to get 8/4" thick lumber. The average wood loss per log, considering the saw kerf and allowance for lumber, is presented in Table 5-23. The wood loss was calculated considering the saw kerf width and allowance for 4/4" thick lumber as 1/8" each. The allowance for 8/4" thick lumber was considered as 3/26". However, this experiment did not consider the log defects, thus requiring some caution in interpreting the results.

Table 5-23: Wood loss on saw kerf and allowance for control and test samples.

	Control			*Test*		
Diameter	N	Average Wood loss	SD	N	Average Wood loss	SD
12	15	18.5%	0.7%	15	12.8%	2.1%
13	15	18.5%	0.6%	18	11.9%	1.7%
14	15	18.6%	0.4%	18	12.0%	1.0%
15	15	18.8%	0.7%	15	12.5%	1.1%

A total of 12,008 bf of NHLA grade lumber from 1317 pieces was recovered from a full-scale study from 126 logs. For all the control samples, only 4/4" thick lumber was produced. For the test sample, 8/4" thick lumber was produced after sawing 4/4" thick lumber from the logs' outer zone. A total of 1,002 lumber pieces were sawn as 4/4" thick, and the remaining 315 pieces were sawn 8/4" thick lumber. NHLA grading of all lumber resulted in more than 70% of the lumber graded as 2 common. Only 14% of lumber was graded as 3 common, less than 2% were below grade, and 15% of lumber was graded as 1 common and better. Also, 4,485 bf was recovered as 8/4" thick SGHL from this experiment. The lumber revenue was greater than 95% for Number 3 and better. Less than 4% of the lumber was graded as an economy grade. Seventy-three percent of the lumber was graded as Number 2 and better grade, including 20% of select structural, 17% of Number 1, and 36% of Number 2 grade lumber. Thus, more than 95% of SGHL produced from this experiment could produce structural grade CLTs, but the cost of the lumber by grade might be a critical factor.

This log yield data can be compared with Allison et al. 's (1987) data for 12" diameter logs reported that about 62% of the lumber volume revenue for the 12" diameter logs was structural grade lumber. Each log was sawn 7/4" thick. This experiment observed about 66% lumber revenue as SGHL when sawn as 8/4" thick lumber. The yield reported was 22.4% Number 1, 62.3% Number 2, and 15.3% Number 3. However, this experiment observed a different yield for 12" diameter, 12-feet-long logs. This log grade group yielded 17% select structural, 9% of Number 1, followed by 22%, 16%, and 1% of Number 2, Number 3, and economy. Allison's (1987) yield report does not consider the log length; some caution should be used when comparing these results.

McDonald et al. 's (1996) yield study from yellow poplar cants reported that almost 89% of the lumber was graded as No 2 and better. Approximately 44% of the lumber was select structural grade, and 25% was graded as Number 1 when SGHL was sawn from graded switch ties. When the mill-run, ungraded cants were sawn, 47% of lumber was graded as Number 2 and better, and less than 25% was graded as Number 1 and better. The yield observed by this experiment was different from the other groups. The difference in yield was due to the sawing differences. McDonald et al. (1996) sawed lumber from the standard dimension cants produced as the final product for other markets, but this experiment sawed the logs to get cants of the maximum size based on wood quality. Thus, there is no uniformity in the cant size from each log, which caused variation in lumber volume and grade.

The SGHL yield from all logs from this experiment was comparable to the yield reported by Moody et al. (1993) for 12-feet-long logs. The logs were sawn with a similar method to obtain all SGHL. However, the results presented excluded economy grade lumber. This experiment used the logs for mixed grading instead of sawing all SGHL from each log. Moody et al. (1993) reported that 22.9% of select structural grade lumber and 13.4% of Number 1 grade lumber were recovered from 12-feet logs. The Number 2 grade lumber percentage was more than 50%, significantly higher than the lumber volume observed by this experiment for Number 2 grade lumber because all higher quality lumber from outer zones were sawn and graded as SGHL.

The lumber value of the SGHL was evaluated based on the production cost of the NHLA grade lumber and the grade relation between NHLA and NELMA grade lumber observed by this experiment. The revenue from mixed grade lumber production compared to only NHLA grade lumber production yielded more revenue for 12”, 14’’ and 15’’ diameter logs for two different lumber production methods evaluated for this study. The test samples' average revenue was only statistically higher for 12’’ 14,’’ and 15’’ diameter logs for both MGLA1 and MGEE lumber production methods. This finding suggests that the sawmill should produce SGHL without an economy grade for improved revenue at the referenced lumber value. Economic grade lumber cannot be used in CLT production, and its production does not help generate higher revenue. The yield observed from this experiment as mixed-grade lumber production based on two discussed methods and log types are presented in Appendix G and Appendix H in Table 9-7 and Table 9-8.

An interesting observation on recovery is observed with 13" diameter logs for mixed grade lumber production as these logs yielded statistically the same revenue for both control and test samples. In the yield and revenue comparison of all diameter groups, the lower observed revenue for diameter 13” logs were mainly attributed to a higher volume of the lower grade lumber and bf loss while grading with NELMA, as shown in Table 5-24.

Table 5-24: Total lumber yield percentage by lumber grade and diameter from test samples

Dia	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*	*S. Selects*	*NO 1*	*NO 2*	*NO 3*	*ECO*
12	2.1	11.2	3.5	20.2	1.6	5.8	0.6	9.5	9.1	21.0	14.5	1.0
13	0.9	9.9	4.5	13.9	0.3	8.2	1.5	3.2	16.7	27.0	12.5	1.5
14	5.2	12.2	1.7	17.9	1.5	5.4	0.9	8.4	5.7	16.4	19.2	5.5
15	2.4	15.4	5.9	20.2	0.5	4.5	0.3	11.8	7.4	21.4	8.8	1.4

For 13’’ diameter test logs, both FAS (0.9%) and 1COM (9.9%), lumber from NHLA grade, and S. Selects (3.2%) from NELMA grade had the lowest yield percentage that had the highest lumber value, which reduced the revenue significantly. The lower revenue from log groups 13’’ diameter was attributed to the combined effect of total lumber volume produced, a lower percentage of higher grade NHLA and NELMA lumber, and unit price of lumber by grade. While applying NELMA grade, some lumber required trimming and ripping to upgrade to a higher grade, which ultimately reduced the total bf.

The revenue comparison of control and test samples without economy grade significantly impacted 13 and 14-inch diameter logs, as shown in Table 9-9 and Table 9-10. The differences in recovery for MGEE and MGLA1 methods were attributed to the lumber yield volume by grade, as shown in

Table 5-25, when the economy grade was eliminated to use NHLA. For diameter 14’’ logs, economy grade lumber elimination added 4.3% of 2 COM and 0.6% of the 3 COM lumber. Diameter 14’’ and 15’’ logs also gained eight bf and four bf of the lumber after eliminating economy grade assigned for required ripping and trimming. Thus, the grade yield percentage from each diameter group and corresponding lumber value of NHLA and NELAM grade lumber contributed to the revenue differences. The negative value in

Table 5-25 indicates an additional lumber volume of NHLA grade lumber after eliminating economy grade.

Table 5-25: lumber yield difference between MGEE and MGLA1 method from this experiment.

Lumber grade	*Diameter*			
	12	13	14	15
FAS/1 COM	0.0%	0.0%	0%	0.0%
2 COM	0.0%	1.5%	4.3%	-0.1%
3 COM	0.0%	0.0%	0.6%	0.0%
BG	1.0%	0.0%	0.8%	1.6%
S. Selects	0.0%	0.0%	0.0%	0.0%
NO 1	0.0%	0.0%	0.0%	0.0%
NO 2	0.0%	0.0%	-0.1%	0.0%
NO 3	0.0%	0.0%	-0.1%	0.0%

This yield study's results provide some insights into producing SGHL from yellow poplar logs. On average, 65% of the lumber from the logs was converted to SGHL. More than 95% of the SGHL produced was of Number 3 and better grade that could be used to manufacture structural grade CLTs. More than 70% of the lumber, on average, was of a grade better than Number 2, so lumber produced in this way could be used to manufacture structural grade CLTs.

In conclusion, producing 2x6 and 2x8 dimension SGHL from YP logs with low-quality wood, as discussed in this experiment, exhibited structural grade lumber quality, and yielded 95% of the lumber as Number 3 and better structural grade according to NELMA grading rules. SGHL from the logs with diameter 12'', 14'', and 15'' generated higher yields and revenue for mixed grade lumber production, but diameter 13'' logs only yielded more lumber volume, not higher revenue. A higher volume percentage of lower grade lumber for diameter 13" logs was the major cause of lower recovery more so than other log groups.

5.4 Summary and Major Findings of the Study

1. There were 18 batches of logs sawn to complete the log yield study, and 1317 lumber pieces were obtained for this experiment. The measured lumber volume from the experiment was 12008 bf when all the lumber was graded using NHLA grading rules. For NHLA grading, 70% of the lumber graded as 2 common, and less than 15% of the lumber graded as 1 common and better. Only 14% of the lumber was graded as 3 common, and the volume of the below-grade lumber was less than 2%.
2. There were 1002 lumber pieces sawn as a 4/4" thick that measured 7353 bf of lumber under the NHLA grading rule. More than 70% of lumber was graded as 2 common, 14% of the lumber was graded as 3 common from the 4/4" thick lumber. The volume of 1 common and better lumber was less than 15%.

3. From all 4655 bf of 8/4" thickness lumber, more than 17% was graded as 1 common and better. More than 68% of the lumber was graded as 2 common, and less than 15% was graded as 3 common and lower.
4. There were 4485 bf of 8/4" thick lumber sawn for this experiment and graded as NELMA grade lumber. Lumber was graded green and rough and the grader assigned the NELMA grade, estimating the required trimming, ripping, and dressing, assuming the current lumber. The observed yields were 73% of Number 2 and better grade lumber, where 20% was graded as structural selects, and 17% as Number 1 grade lumber. Also, 24% of the total bf of lumber was graded as Number 3 grade, and 4% were graded as an economy grade.
5. The average lumber yield was higher for test samples compared to the control samples for each log group. There were 14%, 18%, 32%, and 39% higher yields for logs with 12, 13, 14, and 15-inch diameters, respectively.
6. Production of SGHL substantially reduced the volume of lower grade NHLA lumber for each diameter group. For 12" and 13" diameter logs, SGHL production from cants reduced lower grade lumber to below 32% and 28% from more than 85%, respectively, in test samples. For 14" and 15" diameter logs, lower grade lumber volume from mixed grade lumber production reduced to below 25% and 30% from more than 85% and 78%, respectively.
7. Diameter 12'', 14", and 15" logs yielded significantly higher revenue from the mixed grade lumber production than the control samples at $\alpha=0.05$. Diameter 13'' logs yielded higher lumber volume but not revenue due to the higher percentage of lower grade lumber from both NHLA and NELMA grade.

CHAPTER 6. COMPETITIVENESS OF HARDWOOD CLTs

6 Introduction

CLT’s production cost is the panel's total cost, from design to installation in a structure. The expense of converting raw materials into a final product is collectively defined as the production cost. Production cost includes direct, indirect, variable, and overhead costs of the production process. Numerous factors impact the production cost of CLTs. The industry's size, adopted technology, production efficiency, raw material quality, and many other factors significantly influence production costs. Production cost for this study is defined as the sum of the raw material costs and the processing cost to manufacture CLTs.

Three CLT manufacturers interviewed from Chapter 4 identified multiple factors that contributed to CLT production cost. CLT manufacturing's primary cost components are the design cost, raw material cost, processing cost, transportation cost, and installation cost. Design and installation costs were assumed to be similar for any species; thus, they were a constant for this study. Transportation costs are project-specific and accounted for during the agreement, so they had little impact on production costs. The processing and the CLT panel's raw material costs were identified as a significant primary cost component. Manufacturers have adopted different processes to prepare lumber, finger jointing, lamella layups, press, and computer numerical control (CNC) work, so the cost varied based on adopted technology and work required. Computer numerical control work on CLT panels that included trimming, ripping, drilling, and cutting duct lines for utility access, contributed to production cost.

Each company preferred a highly automated production technology to reduce the production cost. However, only one company visited had a highly automated production line, and the other two had semi-automated production lines. CLT panels are customized products, so it is hard to generalize CLT’s production cost from design to installation based on various projects. The CLT industries interviewed in Chapter 4 were asked for the average cost percentage for different cost factors, as discussed by FPInnovations (2011).

Those companies were only able to provide the average cost of raw material and direct labor. The average production cost observed from all companies is shown in Table 3-5, Chapter 3.

From the CLT mill survey results from Chapter 3 and the literature discussed in Chapter 2, lumber value accounts for 35% to 60 % of the total cost for structural grade CLTs. The industrial-grade CLTs lumber value accounts for 60% to 80% of the total production cost. This cost estimation was based on using commonly available softwood lumber and the CLT mill's production technology. Softwood lumber had a different value based on species and the region where it was being procured. Many CLT mills had produced CLTs from the common lumber species available locally. Thus, results from the CLT mill survey were specific to the lumber species chosen by the company.

The production cost of lumber had the highest discrepancy based on the technology of CLT manufacturing. A report published by FPInnovations (2011) showed that 53% of the total cost comes from lumber value, with lumber's buying cost at $400 per 1000 bf. The simulated production cost of CLTs was estimated at $670/ m^3. The Beck Group (2015) determined the production cost of $465 per cubic meter of finished CLT panels. They estimated the lumber's cost as 59% of total production cost, where the buying cost of lumber was $355 per 1000 bf. Brandt et al. (2019) completed a techno-economic analysis of two hypothetical CLT manufacturing facilities. They estimated that the lumber cost was 35% and 41% for small and large mills, respectively. The CLT mill gate value was determined to be $536 and $652 per cubic meter for large and small size mills, respectively, at the average buying value of $359 per 1000 bf without delivery cost. Thus, there was a higher discrepancy in CLT production cost considering various factors from raw materials to production technology adopted by the industries, so it was difficult to generalize CLT’s production cost.

For an engineering construction, each CLT panel should be manufactured as a customized panel dependent on its position in the whole structure. Thus, each panel's production cost from the same facility with similar raw material may also be different. Based on adopted technology, processing cost at each station (where value-added works are performed) may differ for different species. There is not much information on the variation of each process's cost from different lumber species because CLT mills use only specific lumber species with similar mechanical and physical properties to avoid design failure. Thus, it was only feasible for this study to estimate CLT's manufacturing cost from different lumber species if the cost of all other processes was assumed to remain the same.

There are various methods to estimate and express production costs. One of the practices to express the production cost is the cost percentage of the primary raw material. The primary raw material is the major industry's resource to develop products or services for other industries or the end-user. Primary raw material cost does not include the value-added from production chains; thus, it is a better indicator of pricing the final product (Wilting et al., 2014). Variation in quality and quantity of primary raw material and the yield efficiency of such material determine the final product's cost. In the wood-based construction industry, lumber is the primary raw material; thus, lumber's cost is a good reference to determine the final product's production cost.

None of the CLT mills visited for the interview survey for Chapter 3 produced hardwood CLTs at the time of the visits. In the past, both manufacturers who had used hardwood lumber had not documented the processing variation of using hardwood lumber in the same manufacturing setup. Those CLT mills that had used hardwood lumber could not provide CLT production cost by the process station. Thus, there was no information available on CLT production cost by the station. All CLT mills confirmed that the highest cost for plain CLTs comes from lumber value. However, for customized CLTs, that would decrease as the value-added work increases. A highly automated production line has a higher cost of raw material. However, the raw material's cost for a semi-automated or manual mill decreases as the percentage of the operational cost increases.

Hardwood is not a standard raw material in CLT manufacturing since hardwood lumber is not manufactured for structural use, and hardwood is relatively more expensive than softwood (Grasser, 2015). This statement is true for all higher-grade hardwood lumber. However, there has not been much research on the economic prospect of using low value hardwood lumber. The economic feasibility of using low value hardwood lumber in CLT manufacturing would open additional markets for hardwood lumber and raw material choices for CLT mills. So, it was important to compare the SGHL produced from low value hardwood logs for use in CLT manufacturing, given the current species available in the region that could be used for CLT production. In the US, most hardwood lumber is produced in the eastern and northern regions. Southern yellow pine lumber is mainly produced in the US's southeastern states, and the potential market for SGHL based on supply chain potential should be CLT mills in this region that are using SYP as major lumber types to produce CLTs. Accepting SGHL as a new raw material opportunity must compete with the existing primary raw material choice in terms of cost, so SYP was chosen as the reference lumber species for CLT price comparison. Thus, this research's objective was to determine the CLT cost manufactured from the SGHL and compare it with CLTs from southern yellow pine lumber.

6.1 Methodology

The CLT production cost was evaluated as the cost of the lumber in the total production cost. CLT's production cost information from the mill survey from Chapter 4 was insufficient to find the production cost of the various cost factors. The CLT industries provided only the cost of the lumber, adhesive, and direct labor. The lumber's cost was chosen as the primary cost factor, and CLT production cost was calculated as a percentage of cost carried by lumber value.

The referenced lumber value for all grade lumber from SGHL and SYP was collected in the first step. The lumber value of SGHL used for the log yield study in Table 5-18 from Chapter 5 was used as the referenced lumber value to determine the YP CLTs cost. The SYP lumber value used for CLT production cost was obtained from the Random Length report the last week of June 2020 & Richmond International Forest Products, in the last week of June 2020, presented in Table 6-1. The SYP lumber value was selected for the comparison because it was the common type of lumber to all CLT mills, according to the CLT mill survey from Chapter 3. Additionally, SYP lumber is mainly produced in the southeastern states of the US, and the potential market for SGHL based on supply chain potential should be CLT mills in this region that are using SYP as major lumber types to produce CLTs. Also, accepting SGHL as a new raw material opportunity must compete with the existing primary raw material choice in terms of cost.

Table 6-1: Average value for SYP lumber by grade; Source: Random Length June 2020 & Richmond International Forest Products, June 2020.

Lumber grade	*Average lumber value*
S. Selects	620
Number 1	580
Number 2	460
Number 3	290
Economy	215

In the second step, the specification of the CLTs to be manufactured was defined. Comparing the production cost of CLTs using two different lumber species required manufacturing a similar product using standard technology. Thus, the CLT production process comparing yellow poplar and southern yellow pine lumber was generalized to compare plain CLT panels' production. In this case, only the lumber value would be different based on the grade and species of the lumber selected for selected layups. Evaluation of plain CLT panels for production cost is a standard and practical approach because all panels must go through similar processes and procedures before being fabricated into customized products. There can be multiple combinations of lumber in CLTs, and lumber value depends on the lumber grade and species used. The CLTs production economics were evaluated for three different CLT layers, 3-ply, 5-ply, and 7-ply.

In the third step, the required lumber volume for all types of the CLTs was determined, and this lumber volume was used to determine CLTs production cost based on the value of lumber used to set up a layer by species grade. There were some assumptions and limitations to evaluate the production cost of CLTs. The production cost of the CLTs for this experiment was calculated based on the following considerations:

1. Only 2" x 6" lumber was considered for the lamella. 2" x 8" lumber had a lower value than 2" x 6" lumber, so the cost of lumber in CLTs using 2" x 8" lamella was lower than 2" x 6."
2. The actual thickness and width of individual lumber was considered standard 1.375" and 5.5", respectively. So, the lumber value used for this calculation was the lumber value just before the lamella layups.
3. All lumber was finger-jointed and trimmed to the required length at the time of manufacturing.
4. A CLT panel dimension was considered 40' x 10', the maximum dimension of the US's CLTs currently produced.
5. The CLT production cost was evaluated to assume that 40% of the production cost was contributed by lumber value.

The cost of wood was first calculated based on the volume of the lumber consumed by the CLT. The following formula was used to evaluate the total production cost of the CLT:

$$\textit{The total production cost of the CLT} = \frac{\textit{Total lumber value for given CLT}}{\textit{Perccentage contibution of lumber on toal CLT prodcution cost}}$$

6.2 Observation and Results

6.2.1 The Production Cost of CLTs

There was a difference between the referenced lumber value for SYP and SGHL for all grades. NO 1 grade SGHL was $5 higher than the SYP lumber value. Also, the estimated lumber value of select structural and NO 2 grade lumber from YP were $25 and $90 higher than SYP lumber of the same grade. NO 3 and Eco grade lumber had significantly higher value for SGHL, so they were excluded from further calculation.

As discussed in the methodology, 1.375" thick and 5.5” width lumber was considered for manufacturing CLTs. The dimension of the CLT was defined as 40' long and 10' wide. Thus, the length of lumber on the major axis was 40', and the length of lumber on the minor axis was 10'. Also, 23 pieces of 40' long lumber were calculated in the major axis, and 89 pieces of 10' long lumber were calculated in the minor axis per layer of CLTs. The total volume of lumber in major and minor directions for 3-ply, 5-ply, and 7-ply CLTs is shown in Table 6-2.

Table 6-2: Lumber quantity required to manufacture different layer's CLTs

	Lumber quantity				*CLTs volume*
	Major axis		Minor axis		
CLTs layer	Piece count	bf	Piece count	bf	Cubic meter
3 -ply	46	1160	89	561	4.06
5-ply	69	1739	178	1122	6.75
7-ply	92	2319	267	1683	9.44

There were three possible combinations for manufacturing CLTs from YP lumber produced as SGHL using NELMA grades for only using NO2 and higher-grade lumber. Combination and manufacturing costs for 3-ply, 5-ply, and 7-ply CLTs at 40% cost from lumber value are presented in Table 6-3. With similar layups and combinations, the manufacturing cost of all 3-ply, 5-ply, and 7-ply CLTs from SYP lumber was also evaluated. The production cost of SYP CLTs is presented in Table 6-4.

Table 6-3: CLT manufacturing cost from YP lumber calculated with the assumption that 40% of production cost comes from lumber.

	Lumber layups		*Cost*		
CLTs layer	Major axis	Minor axis	Lumber	CLTs	Per cubic meter
3 -ply	YP S. Selects	YP NO 1	$1,076	$2,690	$662.56
	YP S. Selects	YP NO 2	$1,056	$2,641	$650.49
	YP NO 1	YP NO 2	$987	$2,467	$607.64
5-ply	YP S. Selects	YP NO 1	$1,778	$4,445	$658.52
	YP S. Selects	YP NO 2	$1,739	$4,347	$644.00
	YP NO 1	YP NO 2	$1,635	$4,086	$605.33
7-ply	YP S. Selects	YP NO 1	$2,480	$6,201	$656.89
	YP S. Selects	YP NO 2	$2,421	$6,053	$641.21
	YP NO 1	YP NO 2	$2,282	$5,705	$604.34

Table 6-4: CLT manufacturing cost from SYP lumber calculated with the assumption that 40% of the production cost comes from lumber.

	Lumber layups		*Cost*		
CLTs layer	Major axis	Minor axis	Lumber	CLTs	Per cubic meter
3 -ply	SYP S. Selects	SYP NO 1	$1,044	$2,611	$643.10
	SYP S. Selects	SYP NO 2	$977	$2,442	$601.48
	SYP NO 1	SYP NO 2	$931	$2,326	$572.91
5-ply	SYP S. Selects	SYP NO 1	$1,729	$4,323	$640.44
	SYP S. Selects	SYP NO 2	$1,594	$3,986	$590.52
	SYP NO 1	SYP NO 2	$1,525	$3,812	$564.74
7-ply	SYP S. Selects	SYP NO 1	$2,414	$6,035	$639.30
	SYP S. Selects	SYP NO 2	$2,212	$5,530	$585.81
	SYP NO 1	SYP NO 2	$2,119	$5,298	$561.23

The cost of YP CLTs was 3-7% higher than SYP CLTs at the referenced value. Though the cost for YP CLTs was higher with a 15% profit margin, the production cost difference was within the error limit for producing CLTs from SYP lumber. The comparison graph is presented in Figure 6-1.

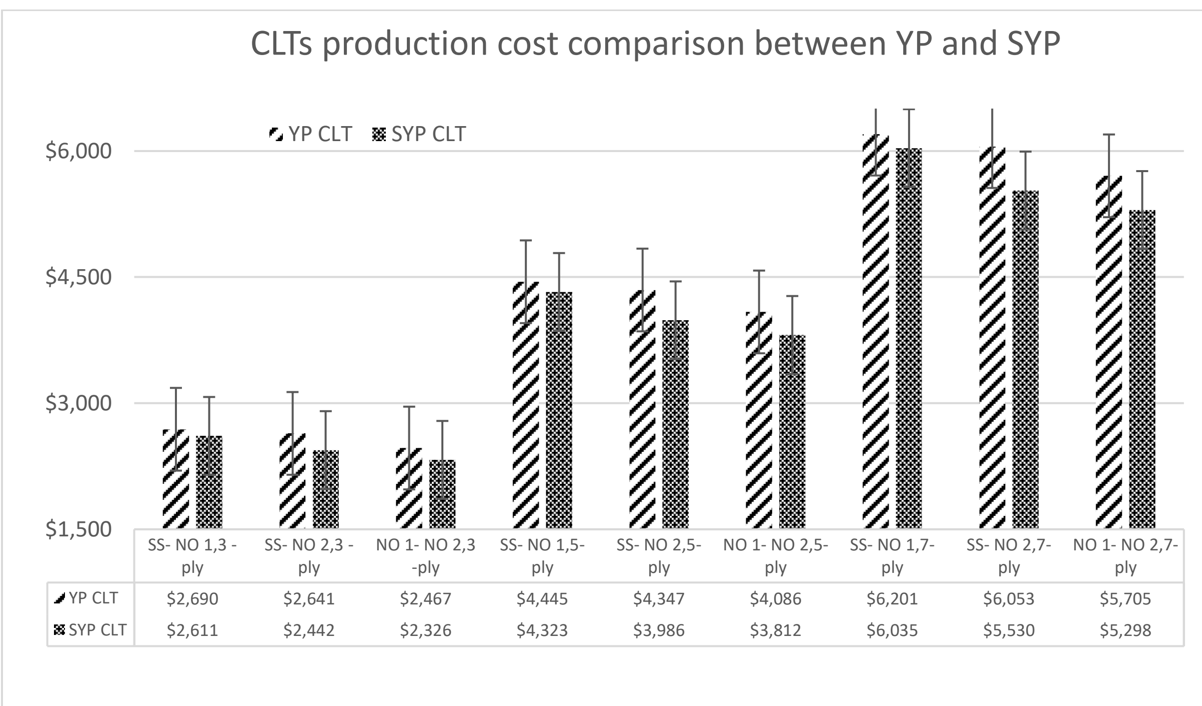

Figure 6-1: Comparison graph for YP and SYP CLT production cost

6.3 Discussion and Conclusions

The production cost of the YP-CLTs was 3-7% higher than SYP-CLTs for all three combinations. All the CLT panel production costs discussed here had 40% of the total cost coming from the lumber. The 3- ply CLT panels were manufactured using S. Selects lumber in a major direction. NO 1-grade lumber in the minor direction from YP had a production cost of $662.56 per cubic meter, which cost only $643.10 when SYP lumber was used. The same 3-ply CLTs, with the lumber combination of YP S. Selects in the major direction and NO 2-grade lumber in the minor direction had a production cost of $650.49 per cubic meter. This CLT production cost was $49.01 higher per cubic meter than when using SYP lumber for a similar combination. For 3-ply CLTs with a lumber combination of NO 1-grade lumber in the major direction and NO 2-grade lumber in the minor direction, the production cost of YP-CLTs was $607.64 per cubic meter. The production cost was 6.1% higher than the SYP-CLTs using a similar combination.

The result to produce both YP-CLTs and SYP CLTs indicated that YP-CLT production had a 6.2% higher production cost, on average. For 3-ply CLTs only, the average production cost of YP CLTs was 5.7% higher than the SYP CLTs. For 5-ply and 7-ply CLTs, the average production cost was 6.4% and 6.6% higher for all combinations.

CLT's production cost from YP and SYP CLTs was evaluated based on the reference value determined from different sources, as discussed in the methods. The production cost was evaluated and compared to 40% of the total production cost with lumber value. Thus, these results have some limitations when applied to other cases due to the lumber price volatility. Some sawmills might not produce SGHL at the provided cost, or some may produce the lumber at a lower cost than discussed here. Also, the SYP lumber value used here was for 10-12-feet longboards, and the value for the lumber was from the eastern US. This calculation excluded the possible variations in lumber value and its weightage on the total production cost. Thus, to address these limitations and find the potential combination of CLT production from YP and other softwood, the production cost at different lumber values and weightage of lumber value on total production cost were evaluated and reduced to linear equations. The minimum lumber value of $400 and a maximum of $750 was used to observe the CLT production cost scenarios for different lumber value. These maximum and minimum lumber values were chosen based on SYP lumber's value published in the second week of June in the Random Lengths Report (Random Lengths, 2020) and the referenced value estimated by FPInnovations (2011). The observed linear equations are presented in Table 6-5, where "MIL" in the equation is the lumber value in the CLT's minor direction. These equations are applicable for determining the CLT production cost for a 40’ x 10’ panel with lumber values from $400 to $750 in the major direction by applying the interpolation method when necessary.

The CLT production cost per cubic meter from YP and SYP from this study is similar to the cost observed by Brandt et al. (2019) and the cost reported by FPInnovations (2011). The minimum production cost observed from this study was \$605/ m^3 and \$561/ m^3 for YP and SYP CLTs, and the maximum was \$663/ m^3 and \$643/ m^3, respectively. In comparison, Brandt et al. (2019) observed \$536/ m^3 and \$652/ m^3 for large and small-sized mills, respectively. This study's CLT production cost was significantly higher than the estimated cost from The Beck Group (2015), which was reported as $465 per cubic meter for finished CLTs. When comparing these results, it is necessary to consider the lumber value used for the calculation. This study assumed that the lumber value was significantly higher than the lumber value used by Brandt et al. (2019) and The Beck Group (2015). Both researchers used lumber values from 2015. However, the value of lumber has significantly increased from 2015 to the present. In 2015, lumber values averaged $350. Now it is approximately $600 (Random Lengths, 2020) per 1000 bf, so CLT’s production cost has continued to increase. Thus, this study's results help to conclude that CLT production cost from YP is 3-7% higher than SYP at the referenced lumber value.

Table 6-5: CLT production cost based on the wood share

Wood share %	*Lumber value major direction*	*3-Ply*	*5-Ply*	*7-Ply*
30 %	400	747.8+3.9*MIL	1495.7+5.8*MIL	2243.5+7.7*MIL
	450	841.3+3.9*MIL	1682.7+5.8*MIL	2524+7.7*MIL
	500	934.8+3.9*MIL	1869.6+5.8*MIL	2804.4+7.7*MIL
	550	1028.3+3.9*MIL	2056.6+5.8*MIL	3084.9+7.7*MIL
	600	1121.8+3.9*MIL	2243.5+5.8*MIL	3365.3+7.7*MIL
	650	1215.3+3.9*MIL	2430.5+5.8*MIL	3645.8+7.7*MIL
	700	1308.7+3.9*MIL	2617.5+5.8*MIL	3926.2+7.7*MIL
	750	1402.2+3.9*MIL	2804.4+5.8*MIL	4206.6+7.7*MIL
40%	400	560.9+2.9*MIL	1121.8+4.3*MIL	1682.7+5.8*MIL
	450	631+2.9*MIL	1262+4.3*MIL	1893+5.8*MIL
	500	701.1+2.9*MIL	1402.2+4.3*MIL	2103.3+5.8*MIL
	550	771.2+2.9*MIL	1542.4+4.3*MIL	2313.7+5.8*MIL
	600	841.3+2.9*MIL	1682.7+4.3*MIL	2524+5.8*MIL
	650	911.4+2.9*MIL	1822.9+4.3*MIL	2734.3+5.8*MIL
	700	981.5+2.9*MIL	1963.1+4.3*MIL	2944.6+5.8*MIL
	750	1051.7+2.9*MIL	2103.3+4.3*MIL	3155+5.8*MIL
50%	400	448.7+2.3*MIL	897.4+3.5*MIL	1346.1+4.6*MIL
	450	504.8+2.3*MIL	1009.6+3.5*MIL	1514.4+4.6*MIL
	500	560.9+2.3*MIL	1121.8+3.5*MIL	1682.7+4.6*MIL
	550	617+2.3*MIL	1233.9+3.5*MIL	1850.9+4.6*MIL
	600	673.1+2.3*MIL	1346.1+3.5*MIL	2019.2+4.6*MIL
	650	729.2+2.3*MIL	1458.3+3.5*MIL	2187.5+4.6*MIL
	700	785.2+2.3*MIL	1570.5+3.5*MIL	2355.7+4.6*MIL
	750	841.3+2.3*MIL	1682.7+3.5*MIL	2524+4.6*MIL
60%	400	373.9+1.9*MIL	747.8+2.9*MIL	1121.8+3.9*MIL
	450	420.7+1.9*MIL	841.3+2.9*MIL	1262+3.9*MIL
	500	467.4+1.9*MIL	934.8+2.9*MIL	1402.2+3.9*MIL
	550	514.1+1.9*MIL	1028.3+2.9*MIL	1542.4+3.9*MIL
	600	560.9+1.9*MIL	1121.8+2.9*MIL	1682.7+3.9*MIL
	650	607.6+1.9*MIL	1215.3+2.9*MIL	1822.9+3.9*MIL
	700	654.4+1.9*MIL	1308.7+2.9*MIL	1963.1+3.9*MIL
	750	701.1+1.9*MIL	1402.2+2.9*MIL	2103.3+3.9*MIL
70%	400	320.5+1.7*MIL	641+2.5*MIL	961.5+3.3*MIL
	450	360.6+1.7*MIL	721.1+2.5*MIL	1081.7+3.3*MIL
	500	400.6+1.7*MIL	801.3+2.5*MIL	1201.9+3.3*MIL
	550	440.7+1.7*MIL	881.4+2.5*MIL	1322.1+3.3*MIL
	600	480.8+1.7*MIL	961.5+2.5*MIL	1442.3+3.3*MIL
	650	520.8+1.7*MIL	1041.6+2.5*MIL	1562.5+3.3*MIL
	700	560.9+1.7*MIL	1121.8+2.5*MIL	1682.7+3.3*MIL
	750	600.9+1.7*MIL	1201.9+2.5*MIL	1802.8+3.3*MIL

6.4 Summary and Major Findings of the Study

1. Only three lumber combinations were used for all 3-ply, 5-ply, and 7-ply panels to compare CLTs' production cost using yellow poplar SGHL and SYP lumber.
2. The 3- ply CLT panels manufactured used S. Selects lumber in a major direction and NO 1 grade lumber in the minor direction from YP had a production cost of $662.56 per cubic meter, which cost only $643.10 when SYP lumber was used.
3. The 3-ply CLTs, with the lumber combination of YP S. Selects in the major direction, and NO 2-grade lumber in the minor direction had a production cost of $650.49 per cubic meter. This CLT production cost was $49.01 higher per cubic meter than when using SYP lumber for a similar combination.
4. The 3-ply CLTs with lumber combination of NO 1-grade lumber in the major direction and NO 2-grade lumber in the minor direction, the production cost of YP-CLTs was $607.64 per cubic meter. The production cost was 6.1% higher than the SYP-CLTs using a similar combination.
5. The result to produce both YP-CLTs and SYP CLTs indicated that YP-CLT production had a 6.2% higher production cost, on average. For 3-ply CLTs only, the average production cost of YP CLTs was 5.7% higher than the SYP CLTs. For 5-ply and 7-ply CLTs, the average production cost was 6.4% and 6.6% higher for all combinations.

CHAPTER 7. DISCUSSION AND CONCLUSION

7 Discussion and Conclusions

The first hypothesis tested was that CLT manufacturers were ready to use hardwood lumber to manufacture CLTs. The results suggested that all three CLT industries visited and interviewed had sufficient technology to produce hardwood CLTs. Two of the sawmills had tried to use hardwood lumber to manufacture CLT mats in their mills. From the two mills' experiences, the existing technology adopted by all three CLT mills was adequate to press hardwood CLTs. However, the variable dimensions of multi-species lumber and lumber quality posed problems in production. The minimum requirements of lumber for CLT manufacturing must be surfaced on all four sides, dried to below 15% moisture content, must be of the same species or have similar strength properties, and should be of standard width and thickness. In general, 2 by X" (where x=4",6",8",10") lumber is used to manufacture CLTs, and the standard dimension choices for the manufacturers are 2 x 6" and 2 x 8" lumber.

The available hardwood lumber for CLT mills was of multiple species with various width types, and many of them were rough and green. That lumber required additional work to prepare and meet the minimum requirements to manufacture CLTs. Such value-added work in CLT mills reduced their productivity. Additionally, the lumber from different species had problems in the press, as the pressure needed to be applied on the panel based on the lumber's strength properties. Cross-laminated timber manufactured with mixed lumber species in the same layer could experience excessive or insufficient pressure on lamella during the adhesion process. Lower or excessive pressure on the lumber face reduces the panel's strength, which is not acceptable for structural application.

The CLT industries also reported quick dulling of cutting tools because of the higher density and some health-related problems due to some hardwood lumber species' caustic nature. However, they did not find them to be significant limitations. Industries could upgrade cutting tools with higher capacity to reduce the dulling of tools and introduce protective gear for employees working with caustic lumber species. The results observed from the CLT mills survey helped conclude that the production of hardwood CLTs was primarily limited by the quality and quantity of lumber available. The current technology adopted by CLT industries was sufficient to produce hardwood CLTs, and the minor problems reported by the industries could be solved with minimum changes in the production process.

The second hypothesis tested was that hardwood sawmills in the US were ready to produce structural grade lumber. The results indicated that very few sawmills had all the resources required to produce SGHL for CLT industries. Around 90% were not currently ready and they need to acquire additional resources to begin production. Hardwood lumber must match the minimum quality of structural grade lumber to use commercially in CLT production. Commercial production of hardwood CLTs requires commercial production of the SGHL.

A survey study was designed to measure the current capacity of hardwood sawmills to produce SGHL. This study yielded a total of 124 complete responses out of the 2040 surveys distributed. The results indicated that many sawmills could saw standard dimension lumber from logs or cants to produce SGHL. However, only 24% of the sawmills could surface all four sides of the lumber. Only 27 % of them had kiln capacity to dry the additional volume of the SGHL. The current ability of the sawmills was measured based on the required resources to begin SGHL production. Forty percent of the sawmills required investment in sawing technology to saw SGHL, 70% of the sawmills required employing a certified lumber grader, and approximately 80% of the sawmills required a planer to surface the lumber.

The commercial production of SGHL required additional investment for most of the sawmills. Most of the sawmills required hiring a certified grader to grade structural lumber and a planer to surface the lumber to produce SGHL that meet minimum CLTs' use requirements. Kiln drying was a limitation for some sawmills, but most sawmills had a sufficient kiln drying capacity. This survey also found that most sawmills were ready to produce SGHL for equal or up to 5% higher revenue than NHLA grade lumber, which indicated the desire of hardwood sawmills to expand their lumber market. Sawmills also responded that many would consider manufacturing SGHL as a product mix with NHLA grade lumber. Both hardwood sawmills and CLT industries could benefit from producing SGHL as a product mix with NHLA grade lumber.

Most of the sawmills were ready to collaborate with other stakeholders to produce SGHL. Collaboration would be crucial for the commercialization of the product. Sawmills that could produce SGHL from species that yield higher revenue could work with other sawmills, lumber manufacturers, or lumber distributors to distribute the lumber efficiently and economically. Collaboration between sawmills would be a benefit for sawing, drying, and dressing the lumber. Sawmills without the capacity to saw standard width lumber could saw cants, and another sawmill could manufacture them into SGHL to sell to CLT mills. Sawmills with limited capacity to dry and plain lumber on all four sides could work together with a sawmill with excess capacity to share the costs and benefits. The collaboration could be more useful in lumber transportation to manufacturers or the CLT mill's inventory if the sawmill had limited production volume. This survey concluded that, at present, less than 10% of sawmills were ready to produce SGHL on a commercial scale. However, the willingness to collaborate with other sawmills and lumber manufacturers to promote SGHL production was a crucial finding.

The third hypothesis tested was that mixed grade lumber production from hardwood species with NHLA grades would yield higher recoveries for sawmills. The log yield study of yellow poplar logs to produce SGHL and NHLA grade lumber as a product mix indicates that mixed grade lumber production yields higher lumber volume due to reduced wood loss. Additionally, diameter 12’’, 14’’, and 15’’ logs produce higher revenue with mixed grade lumber production. Producing SGHL from whole logs was cost-ineffective to sawmills due to NHLA grade lumber's higher value. Production methods to convert lumber from lower quality zones as SGHL helped generate higher revenue for sawmills and reduce lower-grade lumber volume. The critical factor in considering SGHL production was selecting a species that could compete with softwood lumber value and have similar mechanical properties. Thus, YP was chosen as the species for the log yield study. Yellow poplar's physical and mechanical properties are like the lumber types recognized in PRG320 for CLT application, and current lumber values for lower grade lumber are competitive with softwood lumber.

The log yield study was completed by sawing 126 logs with diameters from 12" to 15" and a 12' length of USFS F3 grade to ensure that there were at least 30 logs for each grade group. Higher lumber volume was observed from this experiment in sawing logs to produce lumber mix because sawing 8/4" lumber helped reduce wood loss. As the amount of lumber per log was reduced, the number of saw kerfs was also reduced. Reduced lumber counts also reduced wood loss due to the required sawing allowance for each lumber piece. Production of 8/4," thick lumber reduced the sawing allowance loss to half compared with sawing 4/4" lumber. On average, SGHL production as a product mix increased lumber volume by more than 6 % compared to only 4/4" thick lumber production.

The improved revenue was also due to the reduced volume of lower-grade lumber. Manufacturing SGHL from cants reduced the lower grade lumber volume and converted it into potentially higher value SGHL. On average, 65% of the lumber from the logs was converted to SGHL for all logs. Lower-grade lumber from 2 common and below shrank from 85% to less than 30% when producing SGHL as a product mix with NHLA grade lumber. This reduction in lower grade volume helped in improving the sawmills' revenue.

The lumber value of the SGHL was evaluated using the NHLA grade lumber production cost and grade relation between NHLA and NELMA grade based on observed data from the experiments. For test samples, lumber graded as 1 common and higher from the SGHL group was also evaluated under NHLA grade to maximize the revenue due to the higher value of higher-grade NHLA lumber. There were two factors directly impacting the average revenue. The first factor was the lumber value for lower grade SGHL, and the second factor was the loss of bf while grading SGHL with NELMA rules. When applying the NELMA grade, some lumber required trimming to a reduced length or width or both, which ultimately reduced the total bf and reduced the total revenue.

Observed lumber yield helped to conclude that structural grade hardwood lumber produced from the mixed grade lumber production process exhibited structural grade lumber quality. It yielded 95% of the lumber as Number 3 and better structural grade according to NELMA grading rules. Structural grade hardwood lumber graded as Number 3 and better could be used to manufacture structural grade CLTs. The economy grade lumber obtained from this study could be used to manufacture CLTs for non-structural applications, provided it is economically feasible for CLT industries.

For NHLA and NELMA grade lumber's estimated value as presented in Table 5-18, the observed revenue differences between mix-grade lumber production and NHLA grade alone were only statistically significant for diameter 12’’, 14’’, and 15’’ logs when all 8/4’’ thick lumber with 2 common and below grade were regraded with NELMA grade at $\alpha = 0.05$. When all 8/4’’ thick lumber with 2 common and below grade were regraded with NELMA grade by excluding economy grade, revenue differences between mix grade lumber production and NHLA grade were statistically significant for diameter 12’’, 14’’, and 15’’ logs at $\alpha = 0.05$. This observation concluded that sawmills should avoid using economy grade lumber as it cannot be used to manufacture CLTs for structural application and has higher production cost, as it does not help improve the revenue.

The most critical factor in SGHL production is the production cost, which determines the final lumber value. The SGHL value observed from this yield study in Table 5-18 is different than the lumber value for SYP lumber reported in Table 6-1. The difference between the SYP and the SGHL value is significant for lower grade lumber, as shown in Figure 7-1. Only NO 1 grade lumber had competitive values compared to SYP lumber. Structural selects had a 4% higher lumber value observed by this experiment. NO 2, NO 3, and economy grade SGHL had 20%, 86%, and 126% higher lumber value than SYP lumber’s referenced buying cost. The volume of NO 2 and lower grade lumber was more than 60% in this yield study, so the production cost of the SGHL is crucial to produce YP CLTs. Because NO 3-grade lumber has an 86% higher lumber value than SYP, CLT mills will not choose it as raw material. Thus, the production of hardwood CLTs in the future depends on the production cost of SGHL. The observed results helped to conclude that the referenced lumber value of SGHL could not compete with SYP lumber for CLTs. Only NO 2 and better grade lumber should be evaluated for economic feasibility by individual sawmills.

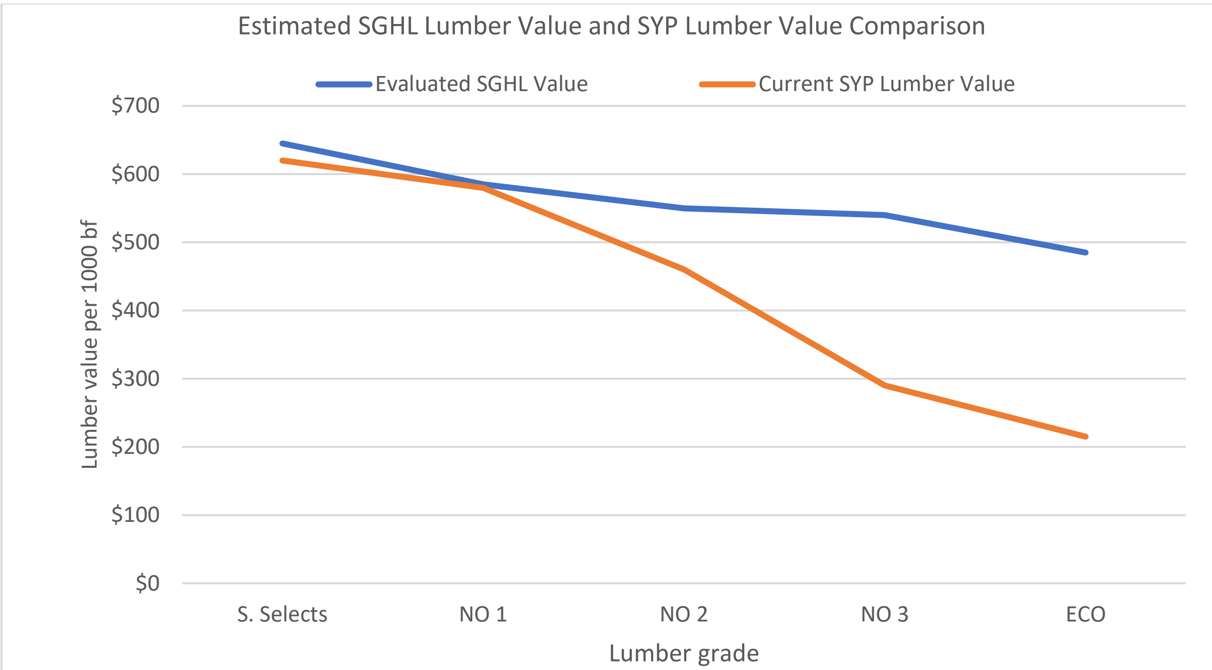

Figure 7-1: Comparison of estimated SGHL value by lumber grade with SYP lumber value from Table 5-18 and Table 6-1

The fourth hypothesis was tested was the assumption that CLTs from SYP and YP are competitive in value. The literature available and data collected from CLT mills visits did not provide enough information on CLT production cost, so the lumber value was used to determine the CLT production cost. Only three lumber combinations were considered for all 3-ply, 5-ply, and 7-ply panels to compare the production cost at 40% from lumber. The results for producing both YP CLTs and SYP CLTs indicated that YP CLT production had a 6.2% higher production cost, on average, at a reference lumber value. For 3-ply CLTs only, the average production cost of YP CLTs was 5.7% higher than SYP CLTs. For 5-ply and 7-ply CLTs, the average production cost was 6.4% and 6.6% higher for all combinations.

This study concluded that CLTs of similar specifications manufactured from YP were 3 to 7% higher than the CLTs from SYP lumber at the reference lumber value in Table 6-1. However, these results should be used with caution because the exact production cost of SGHL on a commercial scale could be different from the findings from this study. Also, the lumber value for SYP was collected in the last week of June 2020. The lumber value was unusual compared to the regular market value. Due to the ongoing pandemic at the beginning of 2020, lumber production and the supply chain were negatively impacted, causing a lumber shortage. The lumber shortage caused a significant spike in value from January to June of 2020 when this study was completed. When CLT mills were visited in 2018-2019, the industries reported that the average lumber cost from SYP was less than $420 per 1000 bf. However, in June of 2020, the lumber value was reported as more than $650 for 1000bf. This lumber value spike of more than 50% had a significant impact on CLT production cost. As the lumber value changes, the cost percentage of the lumber also changes.

In conclusion, from CLT mills' perspectives, hardwood lumber can be marketed as a potential raw material because hardwood CLTs' commercial production is possible using CLT mills' current setup. The only essential requirement is finding a source to supply quality, economically feasible SGHL at a sufficient volume to meet CLT mills demand, but the important factor is the production cost of SGHL. The sawmill survey's critical finding was that very few sawmills were ready to manufacture SGHL, but many were opened to collaborating with other stakeholders, if necessary, to produce SGHL. The willingness of sawmills to collaborate in SGHL production is crucial to commercializing the product. The log yield study results concluded that 2 x 6” and 2 x 8” dimensions of SGHL as the mixed grade from logs core could yield a higher volume of the lumber, but this experiment observed higher revenue from mixed grade lumber production for all diameter logs except diameter 13’’. The log yield study also helped to conclude that the lower grade lumber volume is crucial to recovery, which is the case for diameter 13'' logs in the log yield study. These findings are significant for helping sawmills begin SGHL production from yellow poplar logs, but the production cost of SGHL should also be considered to understand the new product's feasibility. The CLT cost comparison based on YP and SYP lumber values found that YP CLTs costs 3-5% more than SYP CLTs. CLT mills can choose to use YP lumber if it meets the design specifications and has additional economic advantages, but this study did not observe additional economic advantages of using YP lumber rather than SYP at the referenced lumber value.

7.1 Recommendations for Industries

CLT manufacturers have had some experience using hardwood lumber. The major problems with using hardwood lumber were the quality and quantity of the lumber available to them. Hardwood sawmills did not produce lumber to meet the raw material specifications of CLTs. At present, CLT mills had to perform additional work to prepare the lumber before using it. This preparation work added cost and reduced the productivity of the CLT mills. CLT mills wanting to use hardwood lumber and sawmills willing to expand the hardwood lumber market must come together to ensure hardwood CLTs' success. The following recommendations are suggested for both industries.

7.1.1 Recommendation to CLT mills

CLT mills can start using the standard thickness of hardwood lumber to produce CLTs from hardwood lumber. The company should communicate with the hardwood sawmill and ask them to prepare lumber of required specifications based on their current production set up. Using the standard thickness of hardwood lumber will eliminate the adjustments required by sawmills, and sawmills could potentially produce lumber at a reasonable value. Producing CLT mats and hybrid CLTs with hardwood lumber should be the first step to structural grade hardwood CLTs production. Performance tests and specification development of the new product should be appraised before using CLTs for structural application. CLT companies may choose to work together with research institutions to support performance tests and specification development. For commercial use of hardwood, CLT industries and sawmills must work together. Collaboration between hardwood sawmills and CLT industries is critical for hardwood CLT's success. Collaboration would be helpful in the following ways:

1. Sharing production information between sawmills and CLT companies: This practice can help them communicate their needs to each other. Sawmills can produce ready to use lumber so that lumber waste and costs due to raw material preparation can be avoided.
2. Collaboration with a broker, lumber supplier, and lumber distributor: For a CLT company to get ready to use lumber in their inventory, collaboration with brokers, suppliers, or distributors is the best choice to avoid wood waste and increase productivity. If a company needs a large volume of lumber from multiple species, this type of collaboration can be beneficial compared to relying on one to one collaboration with sawmills.
3. Sharing investment to adopt new technology to produce ready to use lumber: CLT companies can collaborate with sawmills to acquire new technology to manufacture SGHL. Currently, SGHL is not produced for the commercial market. CLT mills and sawmills can invest in the required technology, which will minimize investment risk and address both companies' needs.

7.1.2 **Recommendations for Sawmills**

All hardwood sawmills ready to produce SGHL must first figure out the economic feasibility of SGHL production based on their current technology because the production cost and potential lumber value depend largely upon the technology acquired by sawmills. If sawmills decide to produce SGHL, they must reach out to CLT mills to understand their raw material needs and work cooperatively. CLT mills need different lumber thicknesses based on their projects, so working together is essential to find an opportunity to market hardwood lumber in CLTs. Hardwood sawmills that can produce 5/8" to 2" thick lumber have the opportunity to produce lumber for CLT industries. These sawmills could produce 6" and 8" width lumber with single thicknesses based on the CLT mills requirements. CLT mats can be manufactured with any lumber types and species if they meet customer demands and have minimal quality. So, hardwood sawmills should manufacture lumber for CLT mats and continuously evaluate the process to develop a method to convert only lower-grade lumber to SGHL. While manufacturing SGHL, the sawmill should be aware of the standard requirements of lumber for CLT application, which are:

i) Lumber must be produced for uniform width and thickness.

ii) Lumber must be dried to 15% and lower moisture content.

iii) Lumber must be surfaced on all four sides.

iv) Lumber must be graded using structural grading rules.

The YP log yield study results suggest that SGHL produced from the cants potentially yields higher revenue for 12'', 14'', and 15'' diameter logs but not for 13'' diameters logs, if the SGHL produced can be marketed at a price similar to the ones used by this study. However, the observed SGHL production value for lower grade SGHL in Table 5-17 is much higher than the SYP selling price in Table 6-1, so lower grade lumber cannot compete with SYP lumber at all. Thus, sawmills must evaluate the actual production cost of the SGHL to understand the economic competency with other softwood structural grade lumber. With similar production costs and SGHL lumber value, it is not recommended to produce SGHL using current sawmill setups.

For different cost structures of lumber production and lumber value, if the sawmills choose to produce SGHL, they should produce standard width cants and break them into standard width SGHL. Such a method would solve the major lumber dimension challenges of using hardwood lumber in CLTs. As most lower grade lumber comes from the log center, manufacturing SGHL from cants reduces the lower grade lumber volume and converts it into potentially higher yield SGHL, provided mostly higher-grade lumber will be yielded. Again, each sawmill has different technology and production processes, so the SGHL production process should be evaluated to optimize the yield and revenue based on adopted technology.

The standard practice of hardwood lumber production is to saw 1" thick lumber. One inch thick lumber is the accepted thickness for CLT use. So, sawmills should work together with CLT mills to manufacture 1" thick and 6" or 8" width lumber from cants of low-grade logs from some species using their current production setup. All the lumber graded as 2 common and lower and of uniform thickness of standard width should be graded with structural grade and prepared for structural application by drying and dressing. If CLT mills can receive ready to use SGHL, it is easier for them to use hardwood lumber. As suggested by the two CLT mills from Chapter 3, SGHL performs well in CLTs. If there is sufficient lumber available, CLT mills could expand using other thicknesses' lumber after guaranteeing a market. In that case, sawmills could adopt new methods and technology to produce SGHL of other thicknesses, if necessary. Based on the CLT mill’s needs, sawmills can develop a suitable method to produce SGHL. These methods must address the standard requirements for sawmills to produce SGHL for the CLT application. For other lumber thicknesses, there is no additional investment needed for the sawmill to saw standard dimension lumber. Thus, the sawmill can choose to use resawing technology to break cants to produce SGHL.

The survey results from Chapter 4 concluded that many sawmills have two major limitations: first, most sawmills are required to hire a grader to grade SGHL. The second one is to acquire surfacing technology. Both limitations can be solved with minimum investment. If a sawmill could produce enough SGHL, NELMA provides a grading service on a contractual basis. NELMA has a provision to provide grading services four times in a year for a single sawmill, and grading cost is very reasonable with a per-day cost average of $1000. On average, NELMA graders can grade 20 mmbf of lumber per day, so lumber grading adds $20 to the production cost of 1000 bf of lumber. Thus, the sawmill can produce SGHL from the feasible species as a product mix and hire a grader every three months. CLT mills always dress the lumber before applying adhesive, so if sawmills could not surface lumber, both CLT mills and sawmills could work together to find a solution based on economic advantages. Alternatively, sawmills without surfacing capacity could collaborate with another sawmill with the required technology to surface the lumber and share the cost and profit.

7.1.3 **Future Work**

This study graded the lumber as rough and green lumber while applying NELMA grade, so the grade yield and revenue should be reevaluated by applying NELMA grade for ready to use SGHL. This study has no information on the drying process of SGHL, so the study should be designed to test the SDR method discussed in the literature and develop an appropriate method for better yield and revenue of the lumber. AHEC (2019) has reported that the quantity of glue applied to yellow poplar CLTs is 40% higher than softwood CLTs and requires double press time. Thus, such changes in the process and its influence on overall production cost should be considered to determine hardwood CLTs' actual production cost. Thus, a project that starts with the production of the SGHL to fabricate CLTs from the same SGHL should be evaluated at every step to identify the actual value-added work required to produce SGHL and compare the economics of the hardwood and softwood CLTs.

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9 Appendices

Appendix A

CLT Mills Interview Questionnaires

1. What is the current production capacity of your CLT manufacturing unit?
2. What are the different types of CLTs you produce?
3. What are the different grades of the CLT you produce?
4. How many production units are there in your facility?
5. How many CLTs press do you have, and what is their capacity range?
6. Do your production line is automated?
7. What is the production efficiency (%) of your facility in terms of Lumber consumption?
8. $\text{Efficiency} = \frac{\text{Total BF of finished CLTs}}{\text{Total BF of Lumber allocated.}}$
9. What is your production efficiency (%) in terms of machine utilization?
10. $\text{Efficiency} = \frac{\text{capacity utilize}}{\text{Total capacity of the production system}}$
11. What is your inventory capacity of the raw lamella in BF?
12. What is your inventory capacity of Finish goods (BF)?
13. What are the major five softwood species you are using in CLTs?
14. Did your company collaborate with lumber producers to supply the required CLT raw material?
15. Do you receive ready-to-use lumber from all your suppliers?
16. What is your practice to deal with lumber that does not meet the minimum requirements?
17. Suppose your company does not receive ready-to-use lumber from suppliers. What is the additional processing you perform at your facility?
18. Do you have the facility to rework to fix the lumber's non-conformity, and what are the major non-conformity?
19. Does your company use a combination of different lumber species in a CLT panel?
20. Do you ever consider using Hardwood lumber in CLT manufacturing?
21. What are the different hardwood species that you used in CLT manufacturing?
22. With your experience of using hardwood lumber in CLTs; What are the additional processing required to prepare hardwood lumber for CLT use?
23. Did you collaborated or try to team up with hardwood lumber producers to supply lumber ready-to-use in CLTs?
24. Do your company consider using low-value hardwood lumber in CLT manufacturing?
25. What are the problems your company had encountered to use hardwood lumber in CLTs?
26. With your CLT manufacturing, what are the foreseen problems to use low-value hardwood lumber in CLTs?
27. With your experience, what should be considered to begin CLTs from Low-value hardwood lumber?

Appendix B

Hardwood Sawmills Survey Questionnaires

Please provide the information or pick the one that best describes your situation.

1. The percentage of hardwood lumber (by species) produced at our sawmill in 2018:

Hardwood Species	*Approximate percentage of species*
Red Oak	
White Oak	
Yellow Poplar	
Hard Maple	
Soft Maple	
Ash	
Hickory	
Cherry	
Walnut	
Other species	
Total	100%

2. Our overall lumber production capacity (hardwood and softwood) in a million bf for 2018 is:

Below 10 MBF	10-15	16-20	21-25	26-30	31-35	More than 35 MBF

3. Our volume of hardwood lumber production as a percent of total lumber production in 2018 is:

0-10 %	*11-20*	*21-30*	*31-40*	*41-50*	*51-60*	*61-70*	*71-80*	*81-90*	*91-100*

4. Approximate volume of 2 COM and lower grade hardwood lumber as a percentage of total production in 2018:

Less than 35	36-40	41-50	51-60	61-65	66-70	More than 70

5. Our average production cost for the year 2018 to produce 1000 bf of hardwood lumber is:

Less than $200	$201-250	$251-350	$351-450	$451-550	$551-650	More than $650

6. Information on Sawmill capabilities to produce structural grade hardwood lumber:

		Yes	No
a	We can saw hardwood lumber to standard dimensional widths (6", 8" and 10")		
b	We can process hardwood cants of 6-inches to 10-inches width		
c	Our company can surface all four faces of structural grade hardwood lumber		
d	We have adequate dry kiln capacity		
e	We have the excess kiln capacity and can dry an additional volume of lumber		

If you answer "yes" in question 'e' please indicate the available excess capacity (%):

0-10	10-20	20-30	31-40	41-50	51-60	61-70	70-80	81-90

7. Structural grade hardwood lumber is dimensional grade lumber with a standard dimension of 2 by (x). CLT's PRG 320 standard and available hardwood structural lumber grading rules, 2x4, 2x6, 2x8, and 2x10, can be used for CLT manufacturing.

For our mill to enter the hardwood structural lumber grade market, we require the minimum annual demand of lumber to be (in a million BF):

Below 1 MBF	1	2	3	4	5	6	7	More than 10 MBF

8. Information on structural grading and capabilities of our sawmill:

		Yes	No
a.	We are aware that certain hardwood species can be used for structural applications		
b.	Our company is aware that grading agencies such as NELMA, NSLB, or WWPA have developed rules for grading hardwood lumber for structural applications		
c.	Our lumber graders are capable of grading hardwood lumber using structural grades		

9. The expected demand for CLT in the US will require about 200 million bf of lumber by 2020. The CLT manufacturing facility's efficient and economical operation is crucial to establish a sustainable supply of quality raw material. Please answer the following questions regarding the supply of hardwood lumber to the CLT industry.

a. Our sawmill will consider producing structural grade lumber if we can sell for (Please mark the minimum):

- ☐ Equal to the same value as NHLA grade lumber
- ☐ Up to 5% higher value as NHLA grade lumber
- ☐ 5% to 10% higher value as NHLA grade lumber
- ☐ 10% to 15% higher value as NHLA grade lumber
- ☐ 15% or higher value as NHLA grade lumber

b. For Equal or below 5% higher value as NHLA grade lumber, our company will choose the following production strategies (Please mark all that apply to your company):

- ☐ Producing only structural grade lumber for certain species of log grade
- ☐ Producing both structural grade lumber and NHLA grade lumber as product mix
- ☐ Producing standard hardwood cants of 6-inches to 10-inches width
- ☐ We are not interested in producing structural grade lumber for the CLT markets.

c. For 5% or higher value as NHLA grade lumber, our company will choose the following production strategies (Please mark all that apply to your company):

- ☐ Producing only structural grade lumber for certain species of log grade
- ☐ Producing both structural grade lumber and NHLA grade lumber as product mix
- ☐ Producing standard hardwood cants of 6-inches to 10-inches width
- ☐ We are not interested in producing structural grade lumber for the CLT markets.

d. Opportunities to collaborate with other sawmills and CLT manufacturers:

		Yes	No
a	We would consider collaborating with other hardwood sawmills to meet the forecasted demand of CLT manufacturers		
b	We would consider employing a certified hardwood lumber grader and share with another sawmill (s)		
c	We would consider sharing the information on the production and quality of the lumber with CLT manufacturers(s)		

d	We would consider collaborating with the broker(s) and lumber distributor(s) or supplier(s) to market hardwood structural grade lumber		
e	We would consider investment from CLT industries to acquire the necessary capacity (equipment, staff, training, etc.) to produce an increased volume of hardwood lumber		

10. To produce CLTs standard structural grade hardwood lumber, our company must acquire additional resources, equipment, and capacity such as:

		Yes	No
a	Equipment to produce standard width lumber		
b	Certified grader for structural hardwood lumber		
c	Additional sorting capacity		
d	Kiln capacity		
e	Planner to surface all four sides		
f	Additional lumber storage capacity		
g	Other needs (please list here)		

11. Please provide other thoughts not included in this survey that you consider would help you produce hardwood lumber for making CLTs. (Please use an additional sheet if needed.

Appendix C

Shear Analogy Formulas to Calculate CLTs Performance

1 To measure the flatwise bending moment of a CLT panel, the following formula is applied

For the Major Strength direction:

$$(F_b, S)_{eff,f,0} = \frac{0.85 * F_{b,\,major} * S_{eff,f,0}}{12}$$

Where,

$$S_{eff,f,0} = \frac{(EI)_{eff,0}}{E_{major}} * \frac{2}{h}$$

$(F_b, S)_{eff,\,f,0}$ = Effective flatwise bending moment of a CLT, expressed in lbs-ft/ft of width, in the major strength direction

$F_{b,\,major}$ = Bending stress of the lumber in the major strength direction, expressed in psi

$(EI)_{eff,\,f,0}$ = Effective flatwise bending stiffness of CLTs expressed in lbs-ft/ft of width, in the major strength direction

E_{major} = Modulus of elasticity of the lamination, in psi in the major strength direction

h = Gross thickness of CLTs, in inches

For the Minor Strength direction:

$$(F_b, S)_{eff,f,90} = \frac{F_{b,\,minor} * S_{eff,f,90}}{12}$$

Where,

$$S_{eff,f,90} = \frac{(EI)_{eff,90}}{E_{minor}} * \frac{2}{(h - h_1 - h_n)}$$

$(F_b, S)_{eff,\,f,90}$ = Effective flatwise bending moment of CLTs, in lbf-ft/ft of width, in the minor strength direction

F_b, minor = Bending stress of the lumber in the minor strength direction, expressed in psi

$(EI)_{eff,\,f,90}$ = Effective flatwise bending stiffness of the CLT expressed in lbf-ft/ft of width, in the minor strength direction

E_{minor} = Modulus of elasticity of the lamination, in psi in the major strength direction

h_1 = Thickness of the bottom layer of the lamination in inches

h_n = Thickness of the top layer of the lamination in inches

2 To measure the *Flatwise Bending Stiffness* of the CLT panel following formula is applied.

For the Major Strength direction:

$$(EI)_{eff,0} = \sum_{i=1}^{n} E_i w_0 \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i w_0 h_i z_i^2$$

Where,

$(EI)_{eff,\,f,0}$ = Effective flatwise bending stiffness of CLTs, in lbf-in.^{2}/ft (N-mm^2/m) of width, in the CLT major strength direction

E_i = Modulus of elasticity of the lamination in the i-th layer, in psi

w_0 = CLTs width in the CLT major strength direction, expressed in inches of width

h_i = Thickness of laminations in the i-th layer, expressed in inches

z_i = distance between the center point of the i-th layer and the neutral strength direction, expressed in inches

n = number of layers in the CLT

For the Minor Strength direction:

$$(EI)_{eff,90} = \sum_{i=2}^{n-1} E_i w_{90} \frac{h_i^3}{12} + \sum_{i=2}^{n-1} E_i w_{90} h_i z_i^2$$

Where,

$(EI)_{eff,\,f,90}$ = Effective flatwise bending stiffness of CLTs, in lbf-in.2/ft (N-mm2/m) of width, in the CLT minor strength direction

E_i = Modulus of elasticity of the lamination in the i-th layer, in psi

w_{90} = CLTs width in the CLT major strength direction, expressed in inches of width

12.

3 To measure the *Flatwise Shear Rigidity* of the CLT panel following formula was applied.

For the Major Strength direction:

$$GA_{eff,f,0} = \frac{a^2}{\left[\left(\frac{h_1}{2G_1w_0}\right) + \left(\sum_{i=2}^{n-1}\frac{h_i}{G_iw_0}\right) + \left(\frac{h_n}{2G_nw_0}\right)\right]}$$

Where,

$$a = \sum_{i=1}^{n} h - \frac{h_1}{2} - \frac{h_n}{2}$$

$GA_{eff,\ f,0}$ =	Effective flatwise shear rigidity of CLTs, expressed in lbf/ft (N/m) of width, in the major strength direction
G_i =	Modulus of rigidity (shear modulus) of the lamination in the *i*-th layer, in psi
G_1=	Modulus of rigidity of the first layer of CLTs expressed in psi
G_n =	Modulus of rigidity of n^{th} layer of CLTs expressed in psi.

For the Minor Strength direction:

$$GA_{eff,f,90} = \frac{a^2}{\left[\left(\frac{h_1}{2G_1w_{90}}\right) + \left(\sum_{i=2}^{n-1}\frac{h_i}{G_iw_{90}}\right) + \left(\frac{h_n}{2G_nw_{90}}\right)\right]}$$

Where,

$$a = \sum_{i=1}^{n} h - \frac{h_1}{2} - \frac{h_n}{2}$$

$GA_{eff,\ f,90}$ = Effective flatwise shear rigidity of CLTs, in lbf/ft (N/m) of width, in the CLT minor strength direction

13.

4 The following formula is applied to measure the *Flatwise (Rolling) Shear Capacity* of the CLT panel. *For the Major Strength direction:*

$$V_{s,0} = F_{s,minor}\frac{2\ A_{gross,0}}{3}$$

Where,

$$F_{s,minor} = \frac{F_{V,minor}}{3}$$

Vs.,0 = Flatwise shear capacity, expressed in lbf/ft of width in major strength direction

$F_{s,\ minor}$= Planar rolling shear stress of lamination in the minor strength direction

$A_{gross,\ 0}$ = Gross cross-sectional area of CLTs, expressed in square inches of width in major strength direction ($h*w_0$)

For the Minor Strength direction:

$$V_{s,90} = F_{s,major} * \frac{2\ * A_{gross,90}}{3}$$

Where,

$$F_{s,minor} = \frac{F_{V,minor}}{3}$$

Vs.,90 = Flatwise shear capacity, expressed in lbf/ft of width in minor strength direction

$F_{s,\ major}$ = Planar rolling shear stress of lamination in the major strength direction

$A_{gross,\ 90}$ = Gross cross-sectional area of CLTs, expressed in square inches of width in minor strength direction after excluding the outermost layer in both directions [($h-h_1-h_n$) $*w_{90}$]

Appendix D

Performance Results of Major Hardwood Lumber Species

Table 9-1: Shear analogy analysis of red oak for CLT application.

Major Direction	Minor Direction	FbSeff,0	EIeff, 0	GA eff, 0	Vs,0	FbSeff,90	EI eff,90	GA, eff 90	Vs,90
PRG 320 max		4525	115	0.53	1980	165	3.6	0.62	660
PRG 320 min		1740	74	0.35	1160	110	2.3	0.41	385
E1	Red Oak No 2	4531	115	0.46	1815	252	3.12	0.61	605
E2	Red Oak No 2	3834	101	0.46	1815	252	3.12	0.55	605
E3	Red Oak No 2	2789	81	0.45	1815	252	3.12	0.45	605
E4	Red Oak No 2	4531	115	0.46	1815	252	3.12	0.61	605
E5	Red Oak No 2	3834	101	0.46	1815	252	3.12	0.55	605
V1	Red Oak No 2	2091	108	0.46	1815	252	3.12	0.58	605
V2	Red Oak No 2	2033	95	0.46	1815	252	3.12	0.52	605
V3	Red Oak No 2	1743	95	0.46	1815	252	3.12	0.52	605
V4	Red Oak No 2	1801	74	0.45	1815	252	3.12	0.42	605
V5	Red Oak No 2	1975	88	0.45	1815	252	3.12	0.48	605
E1	Red Oak No 3	4530	115	0.43	1815	150	2.86	0.61	605
E2	Red Oak No 3	3834	101	0.42	1815	150	2.86	0.54	605
E3	Red Oak No 3	2789	81	0.42	1815	150	2.86	0.45	605
E4	Red Oak No 3	4530	115	0.43	1815	150	2.86	0.61	605
E5	Red Oak No 3	3834	101	0.42	1815	150	2.86	0.54	605
V1	Red Oak No 3	2091	108	0.42	1815	150	2.86	0.58	605
V2	Red Oak No 3	2033	95	0.42	1815	150	2.86	0.51	605
V3	Red Oak No 3	1743	95	0.42	1815	150	2.86	0.51	605
V4	Red Oak No 3	1801	74	0.41	1815	150	2.86	0.41	605
V5	Red Oak No 3	1975	88	0.42	1815	150	2.86	0.48	605
Red Oak No 1	Red Oak No 2	1917	88	0.45	1815	252	3.12	0.48	605
Red Oak No 1	Red Oak No 3	1917	88	0.42	1815	150	2.86	0.48	605
Red Oak No 2	Red Oak No 3	1859	81	0.42	1815	150	2.86	0.45	605

Table 9-2: Shear analogy analysis of White oak for CLT application.

Major Direction	Minor Direction	FbSeff,0	EIeff, 0	GA eff, 0	Vs,0	FbSeff,90	EI eff,90	GA, eff 90	Vs,90
PRG 320 max		4525	115	0.53	1980	165	3.6	0.62	660
PRG 320 min		1740	74	0.35	1160	110	2.3	0.41	385
E1	White oak No 2	4530	115	0.35	2310	268	2.34	0.59	770
E2	White oak No 2	3833	101	0.35	2310	268	2.34	0.53	770
E3	White oak No 2	2788	81	0.35	2310	268	2.34	0.44	770
E4	White oak No 2	4530	115	0.35	2310	268	2.34	0.59	770
E5	White oak No 2	3833	101	0.35	2310	268	2.34	0.53	770
V1	White oak No 2	2091	108	0.35	2310	268	2.34	0.56	770
V2	White oak No 2	2033	95	0.35	2310	268	2.34	0.50	770
V3	White oak No 2	1742	95	0.35	2310	268	2.34	0.50	770
V4	White oak No 2	1801	74	0.34	2310	268	2.34	0.40	770
V5	White oak No 2	1975	88	0.35	2310	268	2.34	0.47	770
E1	White oak No 3	4529	115	0.32	2310	150	2.08	0.58	770
E2	White oak No 3	3833	101	0.31	2310	150	2.08	0.52	770
E3	White oak No 3	2788	81	0.31	2310	150	2.08	0.43	770
E4	White oak No 3	4529	115	0.32	2310	150	2.08	0.58	770
E5	White oak No 3	3833	101	0.31	2310	150	2.08	0.52	770
V1	White oak No 3	2090	108	0.31	2310	150	2.08	0.55	770
V2	White oak No 3	2033	95	0.31	2310	150	2.08	0.49	770
V3	White oak No 3	1742	95	0.31	2310	150	2.08	0.49	770
V4	White oak No 3	1801	74	0.31	2310	150	2.08	0.40	770
V5	White oak No 3	1975	88	0.31	2310	150	2.08	0.46	770
White oak No 1	White oak No 2	2033	68	0.34	2310	268	2.34	0.37	770
White oak No 1	White oak No 3	2033	68	0.31	2310	150	2.08	0.37	770
White oak No 2	White oak No 3	1975	61	0.30	2310	150	2.08	0.33	770

Table 9-3: Shear analogy analysis of red maple for CLT application.

Major Direction	Minor Direction	FbSeff,0	EIeff, 0	GA eff, 0	Vs,0	FbSeff,90	EI eff,90	GA, eff 90	Vs,90
PRG 320 max		4525	115	0.53	1980	165	3.6	0.62	660
PRG 320 max		1740	74	0.35	1160	110	2.3	0.41	385
E1	Red Maple No 2	4532	115	0.57	2310	284	3.9	0.63	770
E2	Red Maple No 2	3835	102	0.56	2310	284	3.9	0.56	770
E3	Red Maple No 2	2790	81	0.55	2310	284	3.9	0.46	770
E4	Red Maple No 2	4532	115	0.57	2310	284	3.9	0.63	770
E5	Red Maple No 2	3835	102	0.56	2310	284	3.9	0.56	770
V1	Red Maple No 2	2092	108	0.57	2310	283.5	3.9	0.60	770
V2	Red Maple No 2	2034	95	0.56	2310	283.5	3.9	0.53	770
V3	Red Maple No 2	1743	95	0.56	2310	283.5	3.9	0.53	770
V4	Red Maple No 2	1802	74	0.54	2310	283.5	3.9	0.42	770
V5	Red Maple No 2	1976	88	0.55	2310	283.5	3.9	0.49	770
E1	Red Maple No 3	4531	115	0.50	2310	165	3.4	0.62	770
E2	Red Maple No 3	3834	101	0.49	2310	165	3.4	0.55	770
E3	Red Maple No 3	2789	81	0.48	2310	165	3.4	0.45	770
E4	Red Maple No 3	4531	115	0.50	2310	165	3.4	0.62	770
E5	Red Maple No 3	3834	101	0.49	2310	165	3.4	0.55	770
V1	Red Maple No 3	2091	108	0.50	2310	165	3.4	0.59	770
V2	Red Maple No 3	2034	95	0.49	2310	165	3.4	0.52	770
V3	Red Maple No 3	1743	95	0.49	2310	165	3.4	0.52	770
V4	Red Maple No 3	1802	74	0.48	2310	165	3.4	0.42	770
V5	Red Maple No 3	1976	88	0.49	2310	165	3.4	0.49	770
Red Maple No 1	Red Maple No 3	2149	108	0.50	2310	165	3.4	0.59	770
Red Maple No 1	Red Maple No 2	2150	108	0.57	2310	284	3.9	0.60	770
Red Maple No 2	Red Maple No 3	2091	101	0.49	2310	165	3.4	0.55	770

Table 9-4: Shear analogy analysis of yellow poplar for CLT application.

Major Direction	Minor Direction	FbSeff,0	EIeff, 0	GA eff, 0	Vs,0	FbSeff,90	EI eff,90	GA, eff 90	Vs,90
PRG 320 max		4525	115	0.53	1980	165	3.6	0.62	660
PRG 320 min		1740	74	0.35	1160	110	2.3	0.41	385
E1	Yellow Poplar No 2	4531	115	0.50	1485	221	3.38	0.62	495
E2	Yellow Poplar No 2	3834	101	0.49	1485	221	3.38	0.55	495
E3	Yellow Poplar No 2	2789	81	0.48	1485	221	3.38	0.45	495
E4	Yellow Poplar No 2	4531	115	0.50	1485	221	3.38	0.62	495
E5	Yellow Poplar No 2	3834	101	0.49	1485	221	3.38	0.55	495
V1	Yellow Poplar No 2	2091	108	0.50	1485	221	3.38	0.59	495
V2	Yellow Poplar No 2	2034	95	0.49	1485	221	3.38	0.52	495
V3	Yellow Poplar No 2	1743	95	0.49	1485	221	3.38	0.52	495
V4	Yellow Poplar No 2	1802	74	0.48	1485	221	3.38	0.42	495
V5	Yellow Poplar No 2	1976	88	0.49	1485	221	3.38	0.49	495
E1	Yellow Poplar No 3	4531	115	0.46	1485	126	3.12	0.61	495
E2	Yellow Poplar No 3	3834	101	0.46	1485	126	3.12	0.55	495
E3	Yellow Poplar No 3	2789	81	0.45	1485	126	3.12	0.45	495
E4	Yellow Poplar No 3	4531	115	0.46	1485	126	3.12	0.61	495
E5	Yellow Poplar No 3	3834	101	0.46	1485	126	3.12	0.55	495
V1	Yellow Poplar No 3	2091	108	0.46	1485	126	3.12	0.58	495
V2	Yellow Poplar No 3	2033	95	0.46	1485	126	3.12	0.52	495
V3	Yellow Poplar No 3	1743	95	0.46	1485	126	3.12	0.52	495
V4	Yellow Poplar No 3	1801	74	0.45	1485	126	3.12	0.42	495
V5	Yellow Poplar No 3	1975	88	0.45	1485	126	3.12	0.48	495
Yellow Poplar No 1	Yellow Poplar No 2	1685	95	0.49	1485	221	3.38	0.52	495
Yellow Poplar No 1	Yellow Poplar No 3	1685	95	0.46	1485	126	3.12	0.52	495
Yellow Poplar No 2	Yellow Poplar No 3	1627	88	0.45	1485	126	3.12	0.48	495

Appendix E

Log Yield Results from Pilot Study by Log Diameter

Table 9-5: Log yield observed for NHLA grading from the pilot study.

Color Code	Dia	N	FAS	1 common	2COM	Pallet	Total BF
Orange	12	10	168	256	216	87	727
Blue	13	8	131	215	220	6	572
Red	12	9	97	196	260	6	559
Pink	13	7	168	186	129	6	489
White	14	5	83	167	178	7	435
Total		39	647	1020	1003	112	2782
% of Total			23.3%	36.7%	36.1%	4.0%	

Table 9-6: Log yield observed for mixed (NHLA+NELMA) grading from the pilot study.

Color Code	Dia	n	FAS	1 COM	2 COM	Pallet	NO 1	NO .2	NO 3	Total BF
Red	12	9	97	196	141	6	198	18	27	683
Pink	13	7	168	186	84	6	135	9	0	588
White	14	5	83	167	47	7	185	0	60	549
Total		21	348	549	272	19	518	27	87	1820
% of Total			19.1%	30.2%	14.9%	1.0%	28.5%	1.5%	4.8%	

Appendix F

Revenue Recovery Plot per Log from Pilot Study.

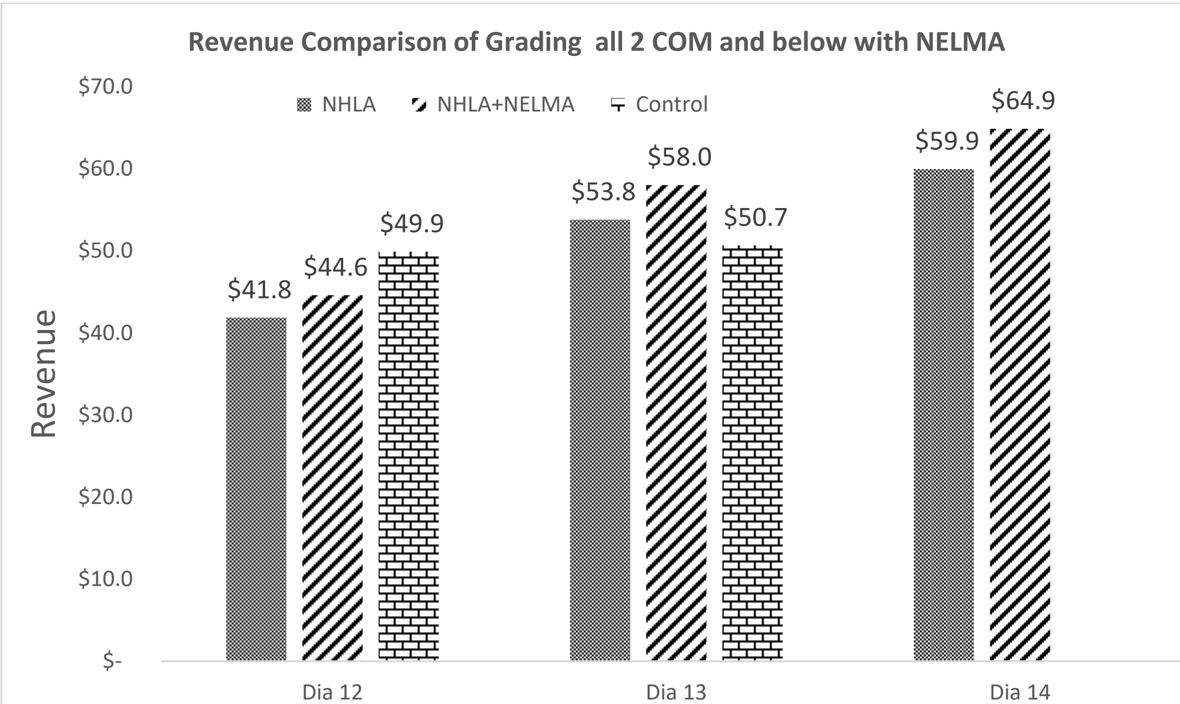

Figure 9-1: Revenue comparison for combined grading only grading 2COM and below with NELMA grading rules

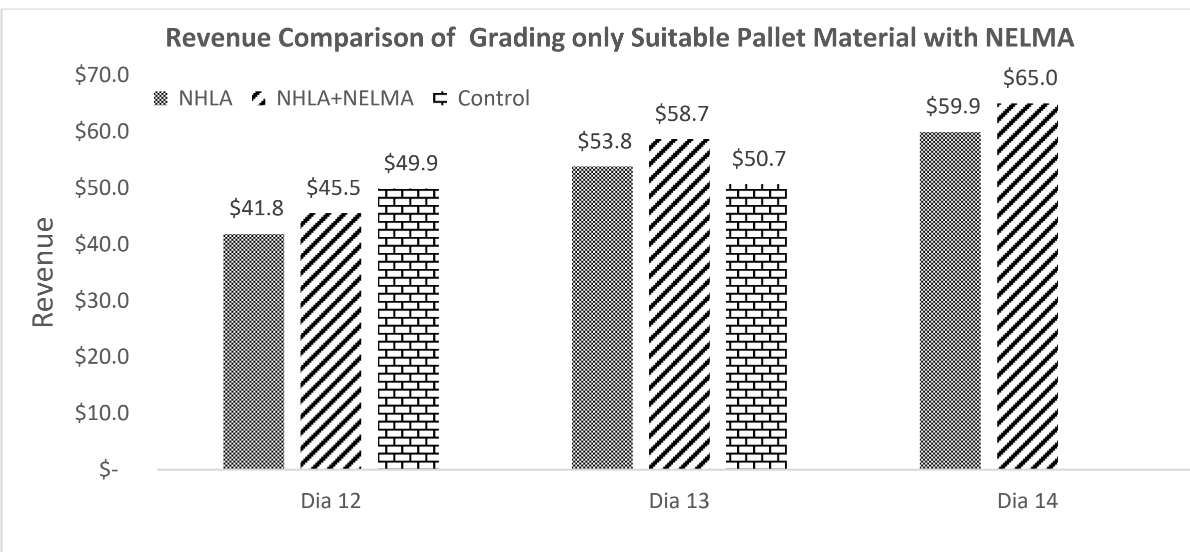

Figure 9-2: Revenue comparison for combined grading of only pallet material with NELMA rules

Appendix G

Log Yield Results from Full-Scale Study by Log Diameter

Table 9-7: Observed log yield from control samples.

Log Diameter	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*	*Total*
12								
			7	48		8		63
			21	32	6	14		73
				70				70
		13		58				71
			7	35	6	14		62
				28	7	28		63
				46	7	7		60
				50		14		64
				54	7	14		75
		7		57				64
				53	9	13		75
			35	35				70
		14	51			15		80
			27	33		7		67
		14	26	22				62
13								
				67	7			74
			7	83		7		97
		8	7	52	9			76
		8		51	20			79

			7	34	20	14	75
			21	30	28		79
				62	6		68
				77			77
		7		41	14		62
		14		44		14	72
				71		14	85
	16	7	35	12		8	78
	17	27	44				88
		8	8	58			74
	14	21	14	14		6	69
14							
				81			81
		28	22	31		12	93
			20	84			104
	7	10	19	49		7	92
		7	32	36	7	7	89
	7	14		65			86
		15	14	60	7	7	103
		15	12	49			76
	6	25		21	7	14	73
				84		7	91
		6		62		6	74
			56			24	80
	6	23	40	14		7	90
		10	25	64			99
		7	81	14			102
15							

		10	21	48	14	18		111
		14	14	56	8			92
			7	99				106
		18		67		7		92
		7	7	56		14		84
		7		65		21		93
			9	70		21		100
	14	25	16	51		7		113
		7	8	77	7	7		106
		15		66				81
		7		59		7		73
	37	35	12	7		7		98
	7	42	47	11				107
		7		90	7	7	7	118
		54	41	5				100

Table 9-8:Observed log yield from test samples.

Log Diameter	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*	*S. SELECTS*	*NO 1*	*NO 2*	*NO 3*	*ECO*	*Total*
12													
				18	6	23		12	12	12	12		95
				4				32	16		16		68
				18		6	6				48		78
				6		8				16	48		78
				22					32	16	16		86
				18					12	36			66
		6		26					12	24	12		80
				13	6	6		12	12	12	12		73
	10			12	6	8		28		12	12		88
				17		4		11		48			80
				19				24	12	10			65
			19			3		10		36			68
	8	8	16	6				24				12	74
		4		19				22		24			69
	6	6		14				24		10	9		69
13													
					4	6			38	16	10		74
			17	12						42	16		87
				16		12	6				54	24	112
				14		8			16	48	16		102
				4		11		16	16	32	16		95
				28				16	16	32			92
		23		8				30	14	12			87
				10		16			16	32	32		106

				20		12		10	12	24			78
				5		18			16	48			87
				10		12	6		12	36	30		106
		6		8		8			29	16			67
	10		6	4		6			12	36	10		84
		10	6	20					12	12	24		84
				17			11	12	12	24			76
			16	16		8			32	32			104
			12	8				16	16	32			84
			11						32	32	16		91
14													
				29					16	32	32		109
		5	7	12	10						26	46	106
				40		5		16			64		125
				24		28				20	48	14	134
				20		14		48		32			114
		6		26				32	16	32			112
				18	3	4				24	36		85
		8	8	20				16	16	36	16		120
				36		17		16		32	32		133
				23			6		32	32	16		109
				36					16		48		100
	8	11						16		32	16	13	96
		8	8	17	13			15		13	45		119
				11		20		13		32		32	108
	6	34						64	13		18		135
		11	12				7	13	16		42		101
	17	8					8	32	32	16	13		126

		24		8		8		16	16	48		16	136
15													
		18	5			13	5	22		24	12		99
		6	17			18			48	16	32	16	153
				54		13				16	64		147
				36		3		32		64			135
		10		37					32	48			127
		8		31				16		64			119
				52		8		32		32	16		140
			17	36				32	16	32	16		149
				35	9			32		48			124
				20		13			16	64			113
		14		29		5		72	16		16		152
		7	25						29	45	32		138
		10	16	18					16	48		16	124
		8	6	22				32	32	16	12		128
	14	6	24					48	12		32		136

Appendix H

Observed Yield and Revenue Recovery from Test Samples

Table 9-9: Observed yield and revenue for test sample with economic grade lumber from SGHL.

Types	Dia	Total bf	Revenue recovered	FAS	1 COM	2A COM	2B COM	3A COM	3B COM	BG	S. Selects	NO 1	NO 2	NO 3	ECO
Test	12	91	$38.27	0	0	0	22	6	24	0	8	10	12	9	0
Test	13	67	$29.06	0	0	0	0	4	14	0	0	30	12	7	0
Test	14	112	$52.81	0	0	0	48	0	0	0	0	5	32	27	0
Test	15	107	$64.99	0	55	8	0	0	16	6	10	0	12	0	0
Test	12	66	$38.49	0	16	0	6	0	0	0	15	16	0	13	0
Test	13	87	$45.23	0	6	20	16	0	0	0	0	0	37	8	0
Test	14	99	$35.13	0	8	10	11	10	0	0	0	0	0	16	44
Test	15	157	$89.48	0	71	19	0	0	19	0	0	16	0	16	16
Test	12	83	$29.14	0	0	0	22	0	6	7	0	0	0	48	0
Test	13	109	$38.87	0	12	0	16	0	12	7	0	0	0	38	24
Test	14	129	$53.40	0	0	0	46	0	8	0	11	0	0	64	0
Test	15	153	$62.01	0	0	0	57	0	16	0	0	0	16	64	0
Test	12	78	$26.78	0	0	0	7	0	8	0	0	0	16	47	0
Test	13	103	$46.35	0	0	0	15	0	8	0	0	16	48	16	0
Test	14	129	$44.52	0	0	0	26	0	28	0	0	0	15	48	12
Test	15	141	$72.72	0	0	0	42	0	8	0	32	0	59	0	0
Test	12	89	$44.81	0	0	0	25	0	0	0	0	32	16	16	0
Test	13	95	$42.58	0	0	0	7	0	13	0	16	11	32	16	0
Test	14	119	$61.19	0	0	0	23	0	16	0	48	0	32	0	0
Test	15	130	$71.39	0	10	0	40	0	0	0	0	32	48	0	0
Test	12	64	$32.86	0	0	0	18	0	0	0	0	12	34	0	0
Test	13	92	$55.24	0	16	0	28	0	0	0	16	16	16	0	0
Test	14	117	$66.51	0	7	0	30	0	0	0	32	16	32	0	0

Test	15	129	$69.32	0	9	0	40	0	0	0	16	0	64	0	0
Test	12	83	$42.78	0	6	0	29	0	0	0	0	12	24	12	0
Test	13	86	$63.99	0	66	0	8	0	0	0	0	12	0	0	0
Test	14	89	$34.29	0	0	0	18	5	6	0	0	0	24	36	0
Test	15	141	$70.87	0	0	0	52	0	9	0	32	0	32	16	0
Test	12	76	$34.64	0	0	0	14	7	7	0	12	12	12	12	0
Test	13	107	$46.59	0	16	0	11	0	16	0	0	0	32	32	0
Test	14	119	$68.94	0	28	8	22	0	0	0	13	16	16	16	0
Test	15	156	$92.11	0	32	21	39	0	0	0	32	0	16	16	0
Test	12	88	$47.34	10	0	0	12	6	8	0	28	0	12	12	0
Test	13	79	$43.23	10	0	0	20	0	13	0	0	12	24	0	0
Test	14	137	$59.86	0	0	0	38	0	19	0	16	0	32	32	0
Test	15	129	$74.71	0	32	0	39	10	0	0	16	0	32	0	0
Test	12	85	$40.96	0	0	0	18	0	8	0	11	0	48	0	0
Test	13	91	$39.51	0	0	0	6	0	21	0	0	16	48	0	0
Test	14	112	$53.50	0	0	0	25	0	0	7	0	32	32	16	0
Test	15	113	$52.65	0	0	0	24	0	14	0	0	11	64	0	0
Test	12	66	$37.95	0	0	0	21	0	0	0	24	12	9	0	0
Test	13	105	$45.39	0	12	0	10	0	12	7	0	12	24	28	0
Test	14	103	$46.83	0	0	0	44	0	0	0	0	16	0	43	0
Test	15	140	$79.32	0	9	0	27	0	9	0	71	13	0	11	0
Test	12	71	$41.28	0	22	19	0	0	6	0	0	0	24	0	0
Test	13	58	$32.31	0	8	0	8	0	6	0	0	29	7	0	0
Test	14	97	$64.95	22	31	0	0	0	0	0	0	0	28	0	16
Test	15	140	$81.45	0	42	27	0	0	0	0	0	16	39	16	0
Test	12	78	$50.51	6	29	22	9	0	0	0	0	0	0	0	12
Test	13	84	$41.58	5	0	5	10	0	6	0	0	12	34	12	0
Test	14	126	$62.58	15	10	8	17	16	0	0	0	0	15	45	0
Test	15	131	$72.75	0	25	17	25	0	0	0	0	16	36	0	12
Test	12	78	$48.13	0	30	0	20	0	0	0	0	0	28	0	0

Test	13	90	$49.48	0	20	8	22	0	0	0	0	16	0	24	0
Test	14	120	$45.01	0	0	0	13	0	27	0	16	0	32	0	32
Test	15	142	$78.00	0	7	8	27	0	0	0	32	32	20	16	0
Test	12	68	$48.61	8	27	0	12	0	0	0	12	0	9	0	0
Test	13	72	$36.25	0	0	0	20	0	0	9	12	12	19	0	0
Test	14	134	$113.65	36	78	0	0	0	0	0	20	0	0	0	0
Test	15	135	$101.92	50	23	21	0	0	0	0	0	16	0	25	0
Test	13	93	$47.43	0	0	16	15	0	8	0	0	22	32	0	0
Test	14	98	$49.03	0	17	10	0	0	0	3	13	17	0	38	0
Test	13	72	$38.56	0	0	12	8	0	0	0	6	16	30	0	0
Test	14	107	$73.79	18	52	0	0	0	0	9	6	0	6	16	0
Test	13	90	$43.92	0	0	10	0	0	0	0	0	32	32	16	0
Test	14	129	$74.99	16	22	0	10	0	8	0	0	16	45	0	12

Table 9-10: Observed yield and revenue for test sample without economic grade lumber from SGHL

Types	*Dia*	*Total bf*	*Revenue recovered*	*FAS*	*1 COM*	*2A COM*	*2B COM*	*3A COM*	*3B COM*	*BG*	*S. Selects*	*NO 1*	*NO 2*	*NO 3*
Test	12	91	$38.27	0	0	0	22	6	24	0	8	10	12	9
Test	13	67	$29.06	0	0	0	0	4	14	0	0	30	12	7
Test	14	112	$52.81	0	0	0	48	0	0	0	0	5	32	27
Test	15	107	$64.99	0	55	8	0	0	16	6	10	0	12	0
Test	12	66	$38.49	0	16	0	6	0	0	0	15	16	0	13
Test	13	87	$45.23	0	6	20	16	0	0	0	0	0	37	8
Test	14	101	$52.37	0	8	26	41	10	0	0	0	0	0	16
Test	15	157	$89.08	0	71	19	0	0	19	16	0	16	0	16
Test	12	83	$29.14	0	0	0	22	0	6	7	0	0	0	48
Test	13	109	$47.39	0	12	0	40	0	12	7	0	0	0	38
Test	14	129	$53.40	0	0	0	46	0	8	0	11	0	0	64
Test	15	153	$62.01	0	0	0	57	0	16	0	0	0	16	64
Test	12	78	$26.78	0	0	0	7	0	8	0	0	0	16	47
Test	13	103	$46.35	0	0	0	15	0	8	0	0	16	48	16
Test	14	131	$45.09	0	0	0	26	0	42	0	0	0	15	48
Test	15	141	$72.72	0	0	0	42	0	8	0	32	0	59	0
Test	12	89	$44.81	0	0	0	25	0	0	0	0	32	16	16
Test	13	95	$42.58	0	0	0	7	0	13	0	16	11	32	16
Test	14	119	$61.19	0	0	0	23	0	16	0	48	0	32	0
Test	15	130	$71.39	0	10	0	40	0	0	0	0	32	48	0
Test	12	64	$32.86	0	0	0	18	0	0	0	0	12	34	0
Test	13	92	$55.24	0	16	0	28	0	0	0	16	16	16	0
Test	14	117	$66.51	0	7	0	30	0	0	0	32	16	32	0
Test	15	129	$69.32	0	9	0	40	0	0	0	16	0	64	0
Test	12	83	$42.78	0	6	0	29	0	0	0	0	12	24	12
Test	13	86	$63.99	0	66	0	8	0	0	0	0	12	0	0
Test	14	89	$34.29	0	0	0	18	5	6	0	0	0	24	36
Test	15	141	$70.87	0	0	0	52	0	9	0	32	0	32	16

Test	12	76	$34.64	0	0	0	14	7	7	0	12	12	12	12
Test	13	107	$46.59	0	16	0	11	0	16	0	0	0	32	32
Test	14	119	$68.94	0	28	8	22	0	0	0	13	16	16	16
Test	15	156	$92.11	0	32	21	39	0	0	0	32	0	16	16
Test	12	88	$47.34	10	0	0	12	6	8	0	28	0	12	12
Test	13	79	$43.23	10	0	0	20	0	13	0	0	12	24	0
Test	14	137	$59.86	0	0	0	38	0	19	0	16	0	32	32
Test	15	129	$74.71	0	32	0	39	10	0	0	16	0	32	0
Test	12	85	$40.96	0	0	0	18	0	8	0	11	0	48	0
Test	13	91	$39.51	0	0	0	6	0	21	0	0	16	48	0
Test	14	112	$53.50	0	0	0	25	0	0	7	0	32	32	16
Test	15	113	$52.65	0	0	0	24	0	14	0	0	11	64	0
Test	12	66	$37.95	0	0	0	21	0	0	0	24	12	9	0
Test	13	105	$45.39	0	12	0	10	0	12	7	0	12	24	28
Test	14	103	$46.83	0	0	0	44	0	0	0	0	16	0	43
Test	15	140	$79.32	0	9	0	27	0	9	0	71	13	0	11
Test	12	71	$41.28	0	22	19	0	0	6	0	0	0	24	0
Test	13	58	$32.31	0	8	0	8	0	6	0	0	29	7	0
Test	14	94	$69.31	22	31	13	0	0	0	0	0	0	28	0
Test	15	140	$81.45	0	42	27	0	0	0	0	0	16	39	16
Test	12	78	$50.21	6	29	22	9	0	0	12	0	0	0	0
Test	13	84	$41.58	5	0	5	10	0	6	0	0	12	34	12
Test	14	126	$62.58	15	10	8	17	16	0	0	0	0	15	45
Test	15	135	$73.21	0	25	17	25	0	0	16	0	16	36	0
Test	12	78	$48.13	0	30	0	20	0	0	0	0	0	28	0
Test	13	90	$49.48	0	20	8	22	0	0	0	0	16	0	24
Test	14	120	$56.37	0	0	0	45	0	27	0	16	0	32	0
Test	15	142	$78.00	0	7	8	27	0	0	0	32	32	20	16
Test	12	68	$48.61	8	27	0	12	0	0	0	12	0	9	0
Test	13	72	$36.25	0	0	0	20	0	0	9	12	12	19	0

Test	14	134	$113.65	36	78	0	0	0	0	0	20	0	0	0
Test	15	135	$101.92	50	23	21	0	0	0	0	0	16	0	25
Test	13	93	$47.43	0	0	16	15	0	8	0	0	22	32	0
Test	14	98	$49.03	0	17	10	0	0	0	3	13	17	0	38
Test	13	72	$38.56	0	0	12	8	0	0	0	6	16	30	0
Test	14	107	$73.79	18	52	0	0	0	0	9	6	0	6	16
Test	13	90	$43.92	0	0	10	0	0	0	0	0	32	32	16
Test	14	133	$75.45	16	22	0	10	0	8	16	0	16	45	0