Producing Structural Grade Hardwood Lumber as a Raw Material for Cross-Laminated Timber: Yield and Economic Analysis

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The economic feasibility of producing structural-grade hardwood lumber (SGHL) that qualifies as a raw material for structurally rated cross-laminated timber (CLT) was examined. 126 yellow poplar logs from diameters 12 to 15 inches were selected and divided into test and control samples. A log yield study was then conducted of the yield and revenue generated when producing lumber graded with National Hardwood Lumber Association (NHLA) rules, SGHL rules, and a mix of both rules (NHLA and SGHL-graded lumber). Producing mix-grade lumber added approximately 27% more revenue than producing NHLA-grade lumber on average if sawmills adopt a cant sawing method. Mix-grade lumber production resulted in 32% of the total volume produced as SGHL and the remaining 68% as NHLA lumber. As a result, 2 Common and lower-grade lumber board footage was reduced to only 29% in test samples and remained converted into SGHL compared to more than 85% of 2 Common and lower-grade lumber boards for control samples. 95% of the SGHL produced as mixed-graded lumber with NHLA-grade lumber met the specifications required to produce structural CLT, and the remaining 5% can be utilized to produce non-structural grade CLTs if they meet the minimum requirement of the materials for CLT production.

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INTRODUCTION

The use of structural-grade lumber has primarily been limited to light-frame structures, which have been limited to contruction of buildings having five stories or less. However, the emergence of mass timber construction has opened new opportunities beyond these limits. Cross-laminated Timber (CLT) industries are expected to become the primary consumers of structural-grade lumber among mass timber producers by 2025 (The Beck Group 2018). It is estimated that the CLT industries will consume more than 17% of the total lumber production volume of 2017 in 2025 (Anderson 2018). This growing demand for CLT presents a need for increased production of structural-grade lumber (Adhikari 2020). Furthermore, mass timber construction, commonly used for mid-rise and high-rise structures, complements rather than competes with light-frame construction, creating additional demand for structural-grade lumber.

Currently, the structural lumber market is dominated by softwood species. In 2017, the United States consumed 38.41 billion board feet of softwood lumber while only producing 24.4 billion board feet, resulting in a deficit of more than 35% (Howard and Liang 2018). It is imperative to explore alternative sources of structural-grade lumber to reduce the dependence on imports and meet domestic demand. Hardwood species, with their surplus availability, offer a viable option to expand the domestic structural-grade lumber market (Adhikari *et al.* 2021). Additionally, hardwoods are more dimensionally stable than softwoods (Wood Handbook, 2010), meaning that they are less likely to expand and contract when exposed to changes in humidity and temperature. This is due to several factors, including the density of the wood, the fiber structure, and the amount of lignin present (Wood Handbook, 2010).

A survey of CLT industries in 2018 showed their willingness to use hardwood lumber for manufacturing panels. The same study also revealed that a sustainable and continuous supply of quality hardwood lumber in the required volume would be a substantial factor for CLT manufacturers to adopt it in their production process (Adhikari *et al.* 2020). The technical feasibility of using hardwood lumber for CLT production has been established, as all CLT mills responding to our survey possessed the necessary technology, and three CLT mills already produced hardwood CLTs as custom products. However, hardwood lumber producers were not necessarily ready to produce lumber for structural applications, citing economic disadvantages, so there is a need to determine the most efficient sawing methods for producing structural grade hardwood lumber (SGHL) and demonstrate its financial advantages compared to National Hardwood Lumber Association (NHLA) grade lumber.

In the US, a surplus of lower-grade hardwood lumber from multiple species is available in the domestic market and has been produced as industrial-grade lumber. The volume of industrial-grade lumber produced in 2017 was more than 54%, and these lumber types are continuously increasing in the sawmills inventory (Buehlmann *et al.* 2017). Harvesting hardwood species, such as yellow poplar, red oak, and white oak, can help expand the domestic lumber market and benefit CLT and sawmill industries. Through reducing the import of structural-grade lumber, increasing the use of domestic products, and promoting sustainable forest management, SGHL production from domestic hardwood species becomes an attractive proposition (Grasser 2015; Howard and Liang 2018; Adhikari *et al.* 2021). For hardwood species to be considered for structural use, they must possess acceptable mechanical properties. Previous studies have shown that some hardwood species, such as yellow poplar, exhibit comparable properties to softwood lumber and have been successfully used in structural applications (Green 2005). However, the market acceptance of SGHL remains a challenge, so there is interest to produce SGHL as a CLT raw material as a new market opportunity. Sawmills need a guarantee that their products will be accepted in the CLT market and generate similar or better revenue than NHLA-grade lumber production to produce SGHL on a commercial scale. Recently, Azambuja *et al.* (2022) evaluated the potential of 2 common and lower NHLA-grade yellow poplar lumber as a CLT raw material using standard 4/4 inch thick lumber and found that a significant portion of the tested lumber exceeded the standard requirements for CLT (Cross-Laminated Timber) manufacturing specifications. This study utilized the material avilabe at sawmills but did not produce the lumber for structural use, so the results are based on remanufacturing the NHLA-grade lumber to produce NELMA-grade lumber.

Assessing the yield and recovery of SGHL is crucial for determining SGHL's economic feasibility as a CLT raw material. Previous yield studies by Denig *et al.* (1984), Koch and Stenglein (1986), and Allison *et al.* (1987) focused on specific methods and species and aimed to produce SGHL for different markets than CLT, so a comprehensive evaluation is necessary to align with current market dynamics and sawing technology. However, Azambuja *et al.* (2022) studied to produce SGHL for the structural market by remanufacturing the NHLA grade lumber focusing on CLTs, which likely cost more and become less competitive in the current market. Additionally, the economics of SGHL production must be examined to ensure that it offers a competitive advantage over existing lumber products. Understanding the market dynamics and profitability will enable sawmills to make informed decisions regarding SGHL production and establish a sustainable market.

This study focused on the production of SGHL as a raw material for CLT manufacturing. The authors aimed to identify the most suitable method for producing SGHL that aligns with CLT manufacturing requirements. The yield and revenue of producing NHLA grade, Northeastern Lumber Manufacturers Association (NELMA) aka NELMA grade (SGHL), and mix-grade (NHLA+SGHL) lumber from the same log inventory at a modern sawmill were evaluated. The specific objectives were a) to compare the economics of producing only NHLA grade lumber *vs.* mix-grade (NHLA+SGHL) lumber, b) to determine the feasibility of remanufacturing NHLA grade lumber into SGHL, and c) to compare the two different methods for commercially producing SGHL at a modern sawmill.

EXPERIMENTAL

The first step involved selecting the appropriate log species and grade. Factors considered for log selection included log availability, market demand for lumber from the species, lumber value, and participating sawmill priority. Higher-quality logs were found to yield higher-grade lumber, but their increased cost made them less suitable for commercial CLT production. The authors focused solely on lower-grade logs to align with sawmill revenue maximization. Lower grade logs have defects including knots, split, rot, insect damage, bark inclusion, *etc.*, making them less valuable and suitable for less demanding applications. Previous research by Ringe (1988) supported the feasibility of producing SGHL from lower-grade logs, as log costs decreased faster than the value of lumber as log grade declined. Based on these findings, F3-grade yellow polar logs were chosen for the log yield study. Faust *et al.* (1990) performed tests on structural-grade lumber produced from yellow polar (YP) cants. The test results exceeded the minimum design values specified in the NDS (National Design Specification) 2012 edition supplement for all lumber grades mentioned. These results further justified the selection of yellow polar logs for SGHL production.

The sawing method identified by Allison *et al.* (1987) was adopted with slight modifications to develop a lumber production method that would meet the requirements for CLT raw materials on modern sawmills. The objective was to produce SGHL as a product mix with NHLA-grade lumber. This approach aligned with sawmills’ interests in converting only lower-grade lumber into SGHL while maintaining the production of higher-grade NHLA lumber.

Materials and Methods

Sample selection

A total of 126 yellow poplar logs were collected with diameters from 12” to 15”, 12 ft long, and USFS Grade F3. A minimum sample size of 30 logs was estimated for each diameter group to measure the differences between test and control samples based on a power analysis on JMP software (JMP®, SAS Institute, Cary, NC, USA) to have up to an 85% chance of detecting a 1 standard deviation difference between the sample means at a significance level of $\alpha = 0.1$. Logs were then divided into two groups, with 15 in each diameter group randomly selected as control samples for manufacturing lumber per the sawmill’s existing practice. Another 15 logs with diameters of 12” and 15” and 18 with diameters of 13” and 14” were selected and sorted as test samples to produce lumber with the proposed new sawing method of mixed-grade lumber production. Each diameter group and sample type were assigned a color code and painted on both faces of the logs to identify the lumber in the process.

Sawing method and processing.

One log each from the test and control samples from all diameter groups made a single batch, and each batch was processed separately to avoid lumber mixup. The last three batches with extra test samples from 13” and 14” diameter logs were sawn in three batches, each with one of 13- and 14-inch diameter logs. The cant-sawing method was employed to convert the logs into lumber. Initially, the logs were slabbed to create a flat edge without cutting jacket boards to maximize the size of the resulting cants. The lumber was then sawn using a resawing machine.

Sawing control sample

- For the control sample, the logs were first sawn to obtain jacket boards until a cant of 6-inches by 6-inches or 8-inches by 8-inches cross-section was remaining. A gang saw was then used to produce 4/4 thick lumber from the cants

Sawing test sample

- For logs in the test sample group, each log was initially sawn to cut 4/4 thick jacket boards, until a (what size cant) is produced. Cants were then sawn in a gang saw to to produce 8/4 thick lumber with widths between 6-inches to 12-inches .

The overall method of log yield study adopted to produce SGHL as a product mix with NHLA-grade lumber is shown in Fig. 1.

Lumber from a single batch was collected, sorted, bundled, and removed from the production line before processing the next batch to prevent mixing. The lumber produced was 4/4 for control samples and 4/4 ~~or~~ and 8/4 for test samples, which is the acceptable thicknesses used in CLTs. The dimension of the lumber was measured to determine if it met the requirements for NELMA (SGHL) grade lumber, considering necessary trimming and ripping to achieve standard dimensions for structural use of a 2-inch increment in width and 2 feet increment in length, which was a 1-inch increment in width and 1-feet increment in length for NHLA grading. It is important to note that the lumber was not physically ripped and trimmed for standard dimensions or remanufactured. However, the grader marked each board to indicate the required trimming and ripping for applying the NELMA grade. The dimensional data and lumber grade were recorded using the grader marking for both control and test lumber types.

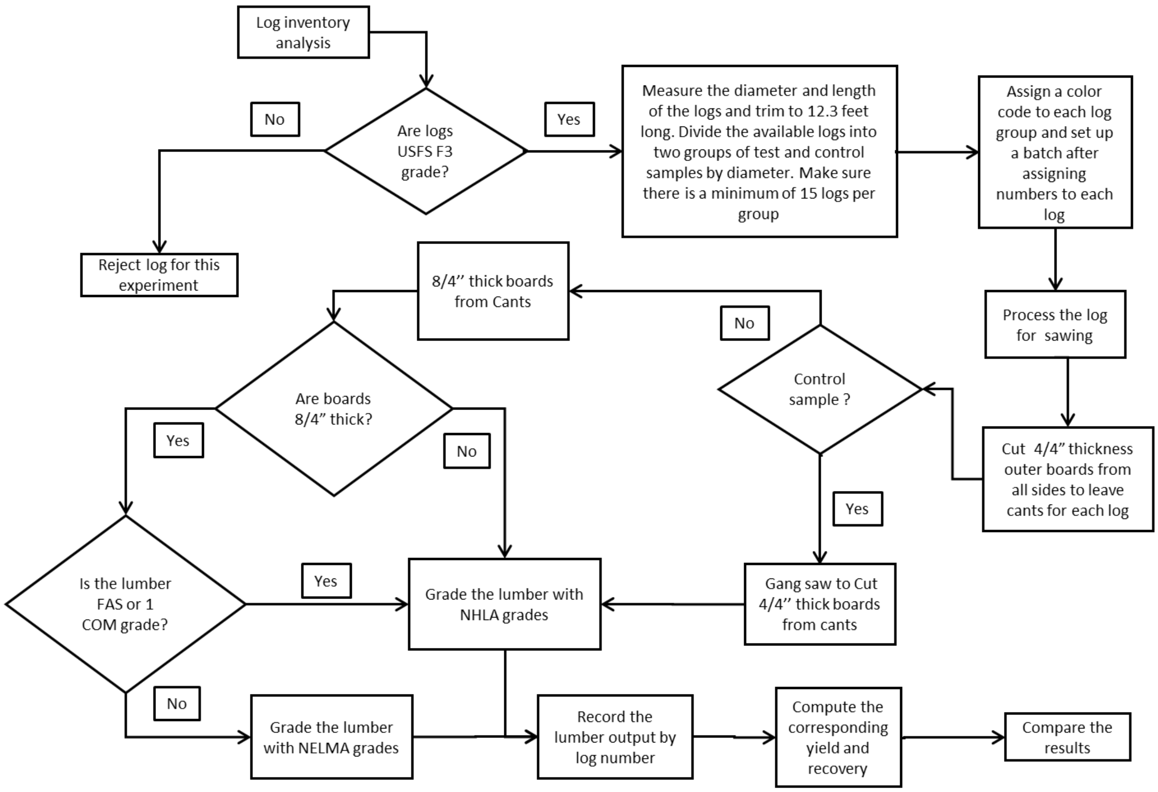

Fig. 1. Overall method of log yield study to produce SGHL as product mix with NHLA grade lumber

Log yield recording

All lumber produced in the log yield study was graded according to NHLA and NELMA standards. Three separate spreadsheets were created to record the lumber output. The first spreadsheet documented the NHLA grades of all lumber produced, including FAS, 1 common, 2A common, 2B common, 3A common, 3B common, and below grade. The second spreadsheet recorded all lumber dimensions and NELMA grades, including Select structural, Number 1, Number 2, Number 3, and Economy grades. The assigned grades were based on estimating the necessary trimming and ripping of the lumber to achieve standard dimensions. The same grading rule was applied to 4/4 and 8/4 lumber, and this information should be considered when interpreting the experiments' results because the size of the defects defines the mechanical properties and visual grading of the lumber. The third spreadsheet recorded mixed grading, where NHLA grades were assigned to all 4/4 and 8/4 lumber graded as 1 common or higher, while NELMA grades were assigned to SGHL with thickness 8/4 and graded as 2 common or lower NHLA grade from sheet one. The lumber outcomes were tallied to determine the total board feet for each log diameter group.

Production cost of SGHL

The value of NHLA grade lumber value was determined based on the Hardwood Market Report (HMR) for June 2020 and information provided by the participating sawmills. The average production cost of 1000 board feet for all lumber grades from yellow poplar was calculated using pricing strategies suggested by Geisel and Hansen (2015) and proportionally distributed to different grades based on various production processes. For SGHL preparation from NHLA-grade lumber, drying, surfacing, and applying NELMA grade were necessary. Initially, the production cost of SGHL was determined without including the cost of preparing the lumber for a structural grade. The lumber was grouped under NHLA grade with the corresponding NELMA grade to establish a relationship between the grades. Based on the yield percentage of NELMA grade from NHLA grade lumber, the production cost of NELMA grade lumber was determined using the reference lumber price of NHLA grade lumber. The drying cost was included in the lumber's NHLA value, and it was assumed that the lumber had a moisture content below 15%. The surfacing cost was assigned as $20 per thousand board feet (MBF), considering it part of the continuous production process. The estimated average cost per day for grading with NELMA was $1,000, assuming the grader could grade 20,000 board feet per day at $20 per thousand board feet of lumber production. Additionally, a 15% profit margin was added on top of the production cost to determine the lumber value of SGHL based on the expected average return from NHLA-grade lumber.

Log yield and economic comparison

Lumber yield from both test and control samples was compared using two-way ANOVA (analysis of variance). The economics of lumber inventory were evaluated at the estimated value for NHLA and NELMA groups and compared for revenue differences. For revenue analysis, the mixed grade method was defined to re-grade only 2 common and lower NHLA grade 8/4 lumber with NELMA. JMP statistical software was used to summarize and analyze the log yield and revenue. Observed yield and revenue were compared using two-way ANOVA at $\alpha = 0.1$.

Identify a commercially feasible method to produce SGHL

The economic return of the two methods to produce SGHL was compared based on observed yield data. The first method was to calculate the volume and value if NHLA-grade lumber was remanufactured to produce SGHL. The second method was to produce mixed-grade lumber with NHLA grade. Thus, the observed lumber yield was evaluated for potential revenue and compared to identify which method produced the highest value of SGHL between the test and control samples.

RESULTS AND DISCUSSION

Lumber Grade and Observed Yield

From the 126 logs, 1317 pieces were sawn, yielding 12003 bf of lumber using NHLA grading rules. For NELMA grading rules, the yield was 10905 bf for the same lumber inventory and 11835 bf when the Mix-grade lumber production method was applied. Grading lumber with NELMA standards involved estimating the trimming and edging required to achieve standard length and width, similar to softwood structural grade. This further processing reduces the total board footage for only SGHL and mix-grade lumber production. The lumber yield was recorded after rounding to the nearest whole number for each piece using the standard mathematical method of rounding to the nearest whole number. If the number observed was exactly 0.5, the lower value was recorded. The distribution of the lumber by all three grading methods, NHLA, NELMA, and MIX Grade, and the corresponding bf of lumber are presented in Table 1, Table 2, and Table 3, respectively. The color used in these tables visually assists in understanding the distribution of lumber volume by grade, as the color gradient toward green means higher volume and towards red means lower volume.

Table 1. Observed Lumber Yield for NHLA Grading Method

LogTypes / Lumber grade	Log Diameter								Total
	12		13		14		15		
	Control	Test	Control	Test	Control	Test	Control	Test	
	N = 15	N = 15	N = 15	N = 18	N = 15	N = 18	N = 15	N = 15	126
FAS	0%	2%	4%	1%	2%	5%	4%	2%	327
1COM	5%	11%	9%	9%	12%	12%	17%	15%	1408
2ACOM	17%	9%	12%	20%	24%	16%	12%	13%	1860
2BCOM	61%	62%	60%	48%	54%	49%	56%	52%	6510
3ACOM	4%	2%	9%	1%	2%	2%	2%	1%	319
3BCOM	13%	12%	5%	17%	7%	14%	8%	14%	1429
BG (Below Grade)	0%	2%	0%	3%	0%	2%	0%	2%	150
Total	1019	1177	1152	1646	1333	2142	1473	2061	12003

Table 2. Observed Lumber Yield for the NELMA Grading Method

LogTypes / Lumber grade	Log Diameter								Total
	12		13		14		15		
	Control	Test	Control	Test	Control	Test	Control	Test	
	N = 15	N = 15	N = 15	N = 18	N = 15	N = 18	N = 15	N = 15	126
S. Selects	24%	26%	21%	10%	27%	22%	29%	24%	2437
NO1	21%	18%	31%	23%	20%	11%	23%	18%	2166
NO2	36%	30%	30%	43%	39%	24%	30%	34%	3580
NO3	18%	24%	18%	21%	13%	32%	15%	21%	2320
ECO	1%	2%	0%	3%	1%	11%	2%	3%	402
Total	866	1119	975	1553	1158	1995	1279	1960	10905

Under NHLA grading, 70% of the lumber by total bf was graded as 2 common, and less than 15% was 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%. Under NELMA grading rules, more than 96% of the lumber by total bf was graded as NO3 and higher, including 75% as NO2 and better, which can be used for structural grade CLT manufacturing. For mix-grade lumber production, about 32% by total bf was graded as SGHL, and the remaining 68% was graded as NHLA-grade lumber.

Table 3. Observed Lumber Yield for the MIX Grading Method

LogTypes / Lumber grade	Log Diameter								Total
	12		13		14		15		
	Control	Test	Control	Test	Control	Test	Control	Test	
	N=15	N=15	N=15	N=18	N=15	N=18	N=15	N=15	126
FAS	0%	2%	4%	1%	2%	5%	4%	2%	327
1COM	5%	11%	9%	10%	12%	12%	17%	15%	1408
2ACOM	17%	4%	12%	4%	24%	2%	12%	6%	1088
2BCOM	61%	20%	60%	14%	54%	18%	56%	20%	4095
3ACOM	4%	2%	9%	0%	2%	1%	2%	0%	267
3BCOM	13%	6%	5%	8%	7%	5%	8%	4%	803
BG	0%	1%	0%	1%	0%	1%	0%	0%	61
S.Selects	0%	9%	0%	3%	0%	8%	0%	12%	576
NO1	0%	9%	0%	17%	0%	6%	0%	7%	640
NO2	0%	21%	0%	27%	0%	16%	0%	21%	1450
NO3	0%	15%	0%	12%	0%	19%	0%	9%	943
ECO	0%	1%	0%	2%	0%	5%	0%	1%	177
Total bf	1019	1163	1152	1579	1333	2072	1473	2044	11835

Lumber yield by log diameter

The lumber yield by log diameter for the control and test samples with NHLA, NELMA, and MIX grades are summarized in Table 4, and the lumber yield distribution and pairwise comparison of the lumber yield for each diameter group by log types are presented in Fig. 2.

Table 4. Observed Average Lumber Yield by Diameter Group for Different Grading Methods Reported as Mean

Log Diameter	Log Types	Number of Logs	NHbf		NMbf		MXbf	
			Mean	SD	Mean	SD	Mean	SD
12	Control	15	68	5.99	58	5.31	68	5.99
12	Test	15	78	9.57	75	8.49	78	8.96
13	Control	15	77	8.57	65	9.05	77	8.57
13	Test	18	91	12.17	86	14.69	88	14.11
14	Control	15	89	10.43	77	9.67	89	10.43
14	Test	18	119	14	111	15.55	115	14.43
15	Control	15	98	12.47	85	12.36	98	12.47
15	Test	15	137	14.08	131	15.24	136	14.08

The variability in the lumber volume was greater for the test group than the control group across all log diameters. Moreover, the standard deviation tended to increase with increasing log diameters, suggesting greater variability in the volume of lumber from larger logs from this experiment. For example, in the control group, the SD (Standard Deviation) for NHbf was 5.99 for log diameter 12 and increased to 12.47 for log diameter 15. Similarly, in the test group, the SD for NHbf was 9.57 for log diameter 12 and increased to 14.08 for log diameter 15. This pattern of increasing variability with increasing log diameters was observed for all lumber yields in both the control and test groups.

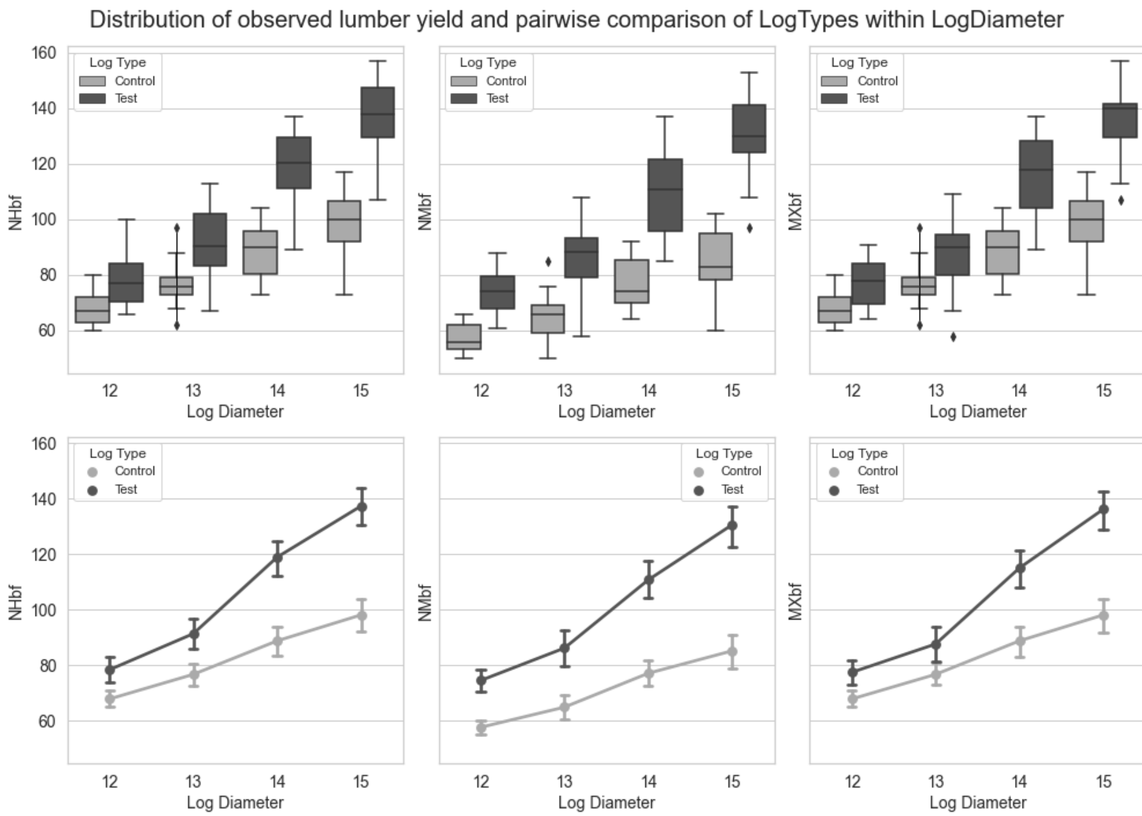

Fig. 2. Lumber yield distribution by log types and diameter and pairwise comparison of yield within log diameter by log types

The average lumber yield for NHLA grading was higher for the test samples than for the control samples. Test logs with diameters 12, 13, 14, and 15 in had 14%, 14%, 30%, and 39% higher lumber yields, respectively. The significance of the differences between test and control samples was studied using two-way ANOVA, and a significant difference (p = < 0.0001) was found between test and control logs on lumber yield. Additionally, the pairwise comparison of the log types within the log diameter was determined, and for all log diameters, there was a significant difference in lumber yield between the test and control logs. For 12" diameter logs, the mean for the control sample was 68 bf; the test sample yielded an average of 78 bf (p = 0.0017) per log. For 13" diameter logs, the control samples had an average yield of 77 bf, and the test samples yielded an average of 89 bf (p = 0.0004) per log. The average log yield for control logs with 14- and 15-inch diameters was observed as 89 bf and 98 bf, whereas for test samples, it was 115 bf (p = < 0.0001) and 136 bf (p = < 0.0001), respectively.

Similarly, the average lumber yield for NELMA grading was compared and was higher and significantly different (p = < 0.0001) for the test samples than for the control samples. Test logs with diameters 12, 13, 14, and 15 in have 29%, 32%, 44%, and 54% higher lumber yields, respectively. The pairwise comparison also indicated significant differences (p = < 0.0001) between log types for each diameter group. The greater difference between the test and control samples for NELMA grading compared to NHLA grading was due to wood loss for the required trimming and ripping of the lumber to obtain the standard width and length for control samples and sawing differences.

The average lumber yield for the Mix grade lumber production was also higher for the test samples compared to the control samples. The ANOVA analysis indicated a significant difference ($p = < 0.0001$) in lumber yield between the test and control samples. Test logs with diameters 12, 13, 14, and 15 in had 14%, 14%, 29%, and 39% higher lumber yields, respectively. For 12" and 13" diameter logs, the observed mean for the control sample was 68 bf and 77 bf; the test sample yielded an average of 78 bf ($p = 0.0017$) and 88 bf ($p = 0.013$) per log, respectively. The average log yield for control logs with 14- and 15-in diameters was observed as 89 bf and 98 bf, whereas for test samples, it was 115 bf ($p = < 0.0001$) and 136 bf ($p = < 0.0001$), respectively.

Analyzing the differences between NHLA and MIX grade lumber production by lumber types demonstrated that the production of SGHL reduced the volume of lower-grade lumber for each diameter group. For 12" and 13" diameter logs, the percentage of lower-grade lumber- 2 common and lower- produced was more than 95% and 87% of total bf yield, respectively, and SGHL as a product mix with NHLA had reduced lower-grade lumber bf to below 32% and 28%, respectively. For the 14" and 15" diameter logs, the lower-grade lumber bf from mixed-grade production shrank below 25% and 30% from more than 86% and 79%, respectively.

This study's results are similar to Allison's (1987) for lumber yield between test and control samples. However, the authors sawed all cants to obtain 8/4 thick lumber, which was different in Allison's study, as they produced 7/4" inch lumber. Table 5 presents the average wood loss per log, calculated considering saw kerf width and allowance for 4/4 and 8/4 thick lumber. The wood loss was estimated as 6.3% higher for the control samples than the test samples evaluated based on the observed saw line for each log. The average lumber yield for the test samples was close to 26% higher than the control samples. It is important to note that log defects were not considered, so caution is necessary when interpreting the results. Other factors that could have contributed to the increased lumber yield for the test samples include differences in sawing setup, log geometry, and rough and green grading of SGHL. Therefore, it is crucial to consider these factors when interpreting the results and drawing conclusions about the experiment's efficacy. It is essential to note that SGHL must be graded after surfacing and drying, which may expose defects not observed during grading rough and green lumber that may change the entire observation of this study and was the study's major limitation.

The authors present log yield data based on log grade, length, and diameter. Comparing these results with past studies is difficult because none explicitly presented log yield reports. However, some comparisons can be made. Allison *et al.* (1987) reported that 62% of lumber volume was structural grade when sawn as 7/4" thick lumber from 12" diameter logs for mixed-grade lumber production, whereas this study observed approximately 66% of lumber volume as SGHL when sawn as 8/4 thick lumber. McDonald *et al.* (1996) reported different yields due to sawing differences, with almost 89% of the lumber graded as No 2 and better and 44% of the lumber as select structural Grade when SGHL was sawn from graded switch ties. Moody (1993) reported that 22.9% of select structural grade lumber and 13.4% of NO1 grade lumber were recovered from 12-ft logs, while this study produced all lumber as SGHL. However, the presented results excluded economy-grade lumber, so estimating the total volume produced by log diameter is impossible. The authors used mixed grading, which resulted in a lower percentage of NO2-grade lumber compared to Moody (1993), who saw all higher-quality lumber from outer zones as SGHL. Overall, the study provides new log yield data that can be partially compared to past studies, but differences in sawing methods and log grading make it difficult to draw a definitive comparison.

Table 5. Wood Loss on Sawn 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%

Economics of a Log Yield Study

Production cost of the NHLA grade lumber

The average production cost for 1000 bf of the lumber from all yellow poplar lumber grades was determined based on the HMR report for June 2020 and the selling value for each lumber grade provided by the participating sawmills of the same period. This selling value was referenced to derive production cost by subtracting the average profit margin, which was assumed to be 15%, as suggested by the sawmills. The cost share for each lumber grade to the nearest multiple of the five is presented in Table 6. The average production cost for 1000 bf of all grade NHLA lumber was determined as $495.

Table 6. Production Cost of the NHLA Grade Lumber by Lumber Grade

Lumber grade	FAS	1 COM	2A COM	2B COM	3A COM	3B COM	BG	Average
Cost Share per 1000 BF ($)	955	685	470	425	325	325	160	495

NHLA and NELMA grade lumber relation

Only lumber with similar dimensions for NHLA and NELMA grades was considered for establishing a relationship between grading rules. Only 436 lumber pieces had similar dimensions for both NHLA and NELMA grades. The NELMA grade lumber distribution by NHLA grade lumber is presented in Table 7. The conversion percentage by each grade was used to develop a linear equation and presented in Table 8. Thus, the linear equation and lumber value by grade were used to estimate the SGHL lumber value.

Table 7. 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%	20%	8%	54%	1%	8%	0%
NO 1	1%	13%	14%	61%	3%	8%	0%
NO 2	1%	11%	11%	59%	1%	16%	1%
NO 3	1%	10%	11%	54%	3%	21%	0%
ECO	0%	5%	5%	42%	5%	32%	11%

Cost of SGHL from YP

The NHLA grade lumber's production cost from Table 5 and the grade conversion equation from Table 8 were used to determine 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 9. The resulting value per 1000 bf of the lumber for all diameter groups was used to compare the economics of mixed-grade lumber production *versus* the existing production practice of the sawmills, as presented in Table 10. The estimated lumber value also includes the drying cost for lower NHLA-grade lumber.

Table 8. 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

Table 9. Production Cost of the NELMA Grade Lumber, Based on NHLA Grade Lumber's Production Cost and NHLA-NELMA Grade Conversion Equation

Lumber Grade	Production Costs up to Drying	Production Cost with Dressing and Grading with NELMA Rule	Lumber Cost with a 15% Profit
S. Selects	520	560	645
NO 1	470	510	585
NO 2	440	480	550
NO 3	430	470	540
ECO	380	420	485

For the economic analysis of the NHLA and NELMA grading practice, NHLA and NELMA grade lumber value was utilized, and for the MIX grade lumber production process, 4/4 thick lumber and FAS or 1 common grade from the test samples were evaluated as NHLA grade. The remaining 8/4 thick lumber was evaluated with NELMA grades and value. A higher value was computed for kiln-dried FAS and 1 common lumber than a structural grade; thus, kiln-dried FAS and 1 common from test samples were evaluated as NHLA grade lumber to optimize the return. All 3 common and lower-grade lumber were also evaluated as dried lumber. Thus, the method to produce SGHL for mix-grade lumber production was chosen to grade only lower than 1 common NHLA grade lumber produced to 8/4 thickness.

Table 10. Referenced Value Used to Calculate the Revenue for NHLA and NELMA-grade lumber

Grading Rules	Lumber State	Lumber Grade	Lumber Value ($)
NHLA	Kiln Dried	FAS	1090
		1 common	795
		2A common	600
		2B common	570
	Green/kiln-dried	3A common	375
		3B common	375
		BG	250
NELMA	Kiln Dried	S. Selects	645
		Number 1	585
		Number 2	550
		Number 3	540
		Economy	485

Log yield return

The revenue by log diameter for the control and test samples with NHLA, NELMA, and MIX grades are summarized in Table 11, and the revenue distribution and pairwise comparison for each diameter group by log types are presented in Fig. 3. Based on the revenue for all grading types, the variability in the value appears to be greater for the test group than the control group across all log diameters. Moreover, the standard deviation tends to increase with increasing log diameter, suggesting greater variability in the lumber value produced from larger logs. For example, in the control group, the SD for NHLA value was $4.78 for log diameter 12 and increased to $11.70 for log diameter 15. Similarly, in the test group, the SD for NH value was $5.18 for log diameter 12 and increased to $13.26 for log diameter 15. This pattern of increasing variability with increasing log diameters was observed in both the control and test groups.

The test samples returned an average of 26% higher revenue for NHLA grading due to their higher lumber yield and lower wood loss than the control samples. Test logs with diameters 12, 13, 14, and 15 inches had 18%, 13%, 32%, and 35% higher revenue, respectively. The significance of the differences between test and control samples was studied using two-way ANOVA, and a significant difference ($p = < 0.0001$) was found between test and control logs on revenue. Further, the pairwise comparison of the log types within the log diameter was determined, and for all log diameters, there was a significant difference in revenue between the test and control logs. For 12” diameter logs, the observed mean for the control sample was $38; the test sample returned an average of $45 ($p = 0.0002$) per log. For 13” diameter logs, the control samples had an average return of $45, and the test samples return an average of $51 ($p = 0.060$) per log. The average return for control logs with 14- and 15-in diameters was $53 and $60, respectively; for test samples, it was $70 ($p = 0.0003$) and $81 ($p = 0.0001$), respectively.

Table 11. Observed Average Revenue for NHLA, SGHL, and Mix-Grade Lumber Production

Log Diameter	Log Types	Number of Logs	NHLA Value		NELMA Value		MIX-Grade Value	
			Mean	SD	Mean	SD	Mean	SD
12	Control	15	$37.50	$4.78	$33.36	$3.32	$37.50	$4.78
12	Test	15	$45.15	$5.18	$43.07	$4.71	$45.70	$5.31
13	Control	15	$45.01	$8.25	$37.63	$5.43	$45.01	$8.25
13	Test	18	$50.78	$8.64	$48.62	$7.71	$50.17	$8.49
14	Control	15	$53.15	$6.92	$44.80	$5.70	$53.15	$6.92
14	Test	18	$70.18	$14.95	$62.54	$10.21	$69.32	$14.69
15	Control	15	$59.95	$11.70	$49.67	$8.06	$59.95	$11.70
15	Test	15	$80.50	$13.26	$75.14	$9.15	$83.20	$12.20

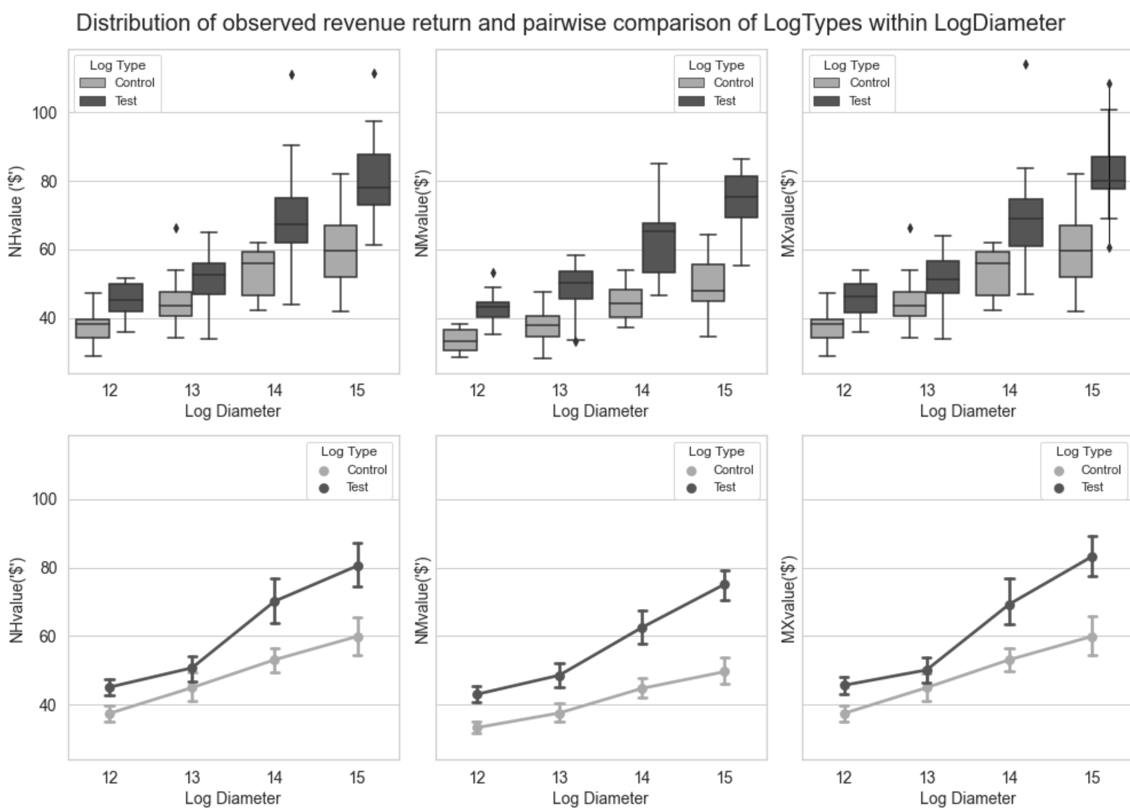

Fig. 3. Revenue distribution by log types and diameter and pairwise comparison of revenue within log diameter by log types

Similarly, the average revenue for NELMA grading was 39% higher and significantly different (p = < 0.0001) for the test samples than for the control samples. Test logs with diameters 12, 13, 14, and 15 inches had 30%, 28%, 40%, and 50% higher revenue, respectively. The pairwise comparison also indicates significant differences (p = < 0.0001) between log types for each diameter group. Test samples had higher revenue because they required minimal wood loss while trimming and ripping the lumber. This is because over 65% of the lumber by volume was manufactured as SGHL of standard dimension. In contrast, control samples required each piece of lumber to be trimmed and ripped to be produced as SGHL, resulting in significant wood loss and lower revenue. Thus, remanufacturing the SGHL from NHLA-grade lumber helps to conclude that remanufacturing NHLA-grade lumber from the open market would not be a viable option for producing SGHL on a commercial scale.

The average revenue for the Mix grade lumber production was also 27% higher for the test samples than the control samples. The ANOVA analysis indicated a significant revenue difference ($p = < 0.0001$) between the test and control samples. If the lumber grade exceeded NO 3, its value was higher than lower-grade NHLA lumber. Test logs with diameters 12, 13, 14, and 15 inches have 21%, 11%, 30%, and 38% higher lumber yields, respectively. For 12" and 13" diameter logs, the observed mean for the control sample was \$38 and \$45; the test sample returns an average of \$46 ($p = 0.0001$) and \$50 ($p = 0.08$) per log, respectively. The average return for control logs with 14- and 15-in diameters was observed as \$53 and \$60, whereas for test samples, the return was observed as \$69 ($p = 0.0004$) and \$83 ($p < 0.0001$), respectively. The test samples had higher average revenue for Mixed grading than the control samples because test samples yielded higher lumber volume, and the study evaluated the lumber sawn to 2" thick dimensions and graded as 1 COM and better as NHLA grade, which adds significant value to higher-grade lumber. If the lumber was lower than 2 COM, it was only evaluated as SGHL. Thus, sawmills can adopt a cant sawing method to produce SGHL as a product mix with NHLA-grade lumber for higher returns than only producing NHLA-grade lumber.

Comparing the two methods identified to produce SGHL commercially

This study compared two methods for producing SGHL: producing SGHL as a product mix and applying the mix grading method *versus* remanufacturing all NHLA-grade lumber to produce SGHL. The analysis showed that log types significantly affected economic returns per log ($p < = 1.22e^{-14}$), and test samples yielded approximately 31% higher revenue on average than control samples. The effect of the lumber production method was significant but much smaller ($p < = 6.44\ e^{-04}$) than log types, and Mix-grade lumber production (MXvalue) generated 12.5% higher revenue than revenue from NELMA grading of lumber (NMvalue), as shown in Fig. 4. Pairwise comparison within each grading group of Mix-grade and NELMA-grade revealed a statistically significant difference in returns for the mix-grading method between log types ($p < = 6.77e^{-06}$) with 27% higher revenue for Test logs and NELMA grading ($p < = 2.85e^{-11}$) with 38% higher revenue for test logs. These findings suggest that remanufacturing lumber would not be a practical method for sawmills, as they may lose wood and revenue unless the lumber is produced to standard dimensions. This study helps to conclude that cant sawing would be the best method for sawmills to produce commercially viable SGHL.

Based on the study results it is recommended to implement a mixed grading system in commercial sawmills, combining NHLA, NELMA, and MIX grading methods for profit maximization. This strategy entails careful log selection, using cant sawing, and producing a mix of SGHL and NHLA-grade lumber. Emphasizing quality control to meet CLT material standards, such as NO3 or higher grades for SGHL, is crucial. It is recommended to regularly assess the economic feasibility of this system to make adjustments as needed for each sawmill. Promoting SGHL as a cost-effective CLT raw material and adopting a mixed grading system in sawmill operations can boost revenue, making it a practical choice for commercial success.

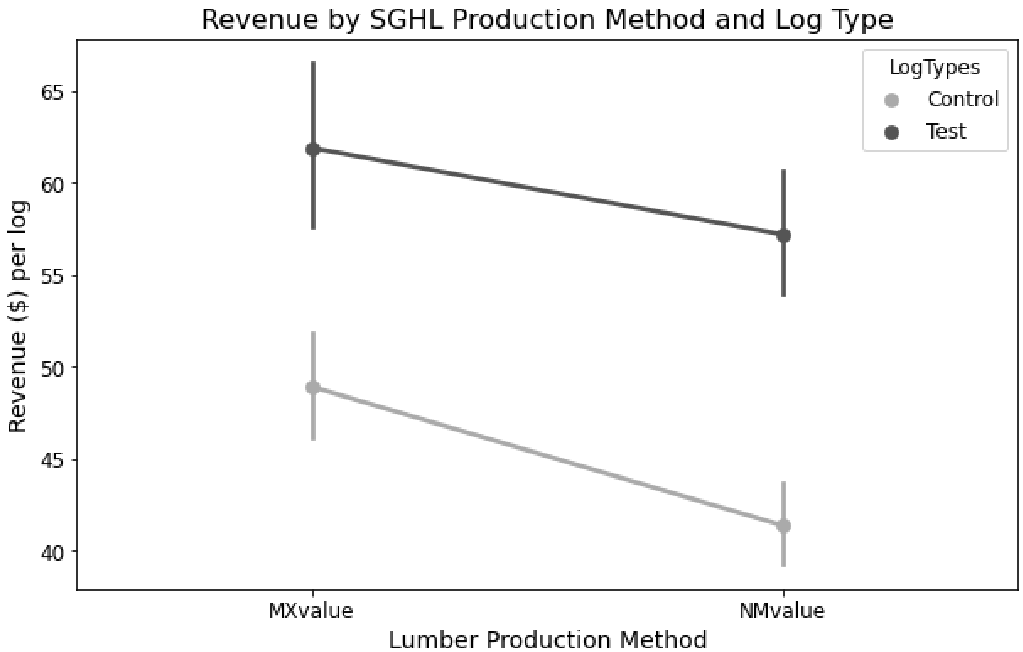

Fig. 4. Revenue comparison for identifying the best method to produce SGHL commercially

CONCLUSIONS

1. The study aimed to investigate the lumber yield produced from different grading methods, including National Hardwood Lumber Association (NHLA), Northeastern Lumber Manufacturers Association (NELMA), and MIX (NHLA and structural grade hardwood lumber) grades, using 126 logs and concludes that producing Mix-grade lumber and adopting the cant sawing method can generate more revenue for sawmills to produce SGHL as a cross-laminated timber (CLT) raw material. Mix-grade lumber production adds approximately 27% more revenue than only producing NHLA-grade lumber when the cant sawing method is adopted to convert the lower-grade lumber into SGHL.
2. Remanufacturing SGHL from NHLA-grade lumber increases the wood loss from trimming and ripping for standardizing the lumber dimension. Thus, the production of SGHL from NHLA-grade lumber from the open market adds costs to CLT manufacturing.
3. Compared to remanufacturing SGHL from NHLA-grade lumber, producing SGHL as a product mix with NHLA-grade lumber can increase the sawmills' revenue by more than 30%, so mix-grade lumber production has been identified as the best method for sawmills to produce SGHL.
4. Mix-grade lumber production resulted in approximately 32% of the total volume being graded as SGHL and the remaining 68% as NHLA-grade lumber. NELMA grading of the SGHL resulted in more than 95% of the lumber being graded as NO3 or higher, with 70% being graded as NO2 or better, which meets the requirements of the CLT raw material and reduces the volume of the lower-grade lumber significantly. For control samples of NHLA grading, the average volume of the 2 Common and lower-grade

lumber was approximately 85%, which shrunk to approximately 29% from mix-grade lumber production. Thus, mix-grade lumber production benefits the sawmill by converting lower-value lumber to higher-value SGHL for the new market, providing additional economic market opportunity.

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