An Evaluation of Low-Grade Red Oak and Soft Maple as Raw Material for Cross-Laminated Timber Panel Production

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Abstract

Utilization of hardwoods in the manufacture of cross-laminated timber (CLT) faces many challenges, one of which is the selection of raw material that is both technically and economically feasible. From an economic perspective, it would make sense to choose species and grades that are both readily available and relatively competitive with softwood species currently used in CLT manufacturing. For the purposes of this study, lower grades (2A Common, 2B Common, 3A Common, and 3B Common) of red oak and soft maple were deemed appropriate in fitting this profile.

All lumber was visually graded according to both National Hardwood Lumber Association (NHLA) and Northeastern Lumber Manufacturers Association (NeLMA) grading rules, as well as nondestructively tested through flatwise bending to determine modulus of elasticity (MOE). The yield distribution of each species and NHLA grade, by visual structural grade, were analyzed. The mechanical testing of each species was analyzed based on the minimum allowable MOE of 1.2 x 10^6 psi as required by ANSI/PRG-320. Mechanical testing resulted in much higher yields of acceptable CLT material than visual grading, for both species.

A total net worth analysis was conducted to evaluate the value of NHLA graded lumber being processed into structurally graded lumber for both species and both grading methods. Finally, a procurement analysis was conducted to determine the volume of lumber required for both species, in order to achieve a fixed volume of CLT-ready lumber.

Introduction

The Appalachian Hardwood Center (AHC) at West Virginia University (WVU) has been engaged in a comprehensive research program exploring the feasibility of utilizing hardwoods in the production of cross-laminated timbers (CLTs). The challenges associated with hardwood CLTs have been well documented by Hassler et al. (2022) and provide a roadmap for investigating the feasibility of hardwoods in CLT manufacturing. One of the challenges highlighted by Hassler et al. (2022) is in selecting the best available hardwood raw material for CLT production. While the softwood CLT industry is blessed with readily available lumber with the standard dimensions and structural grades, and kiln-dried to specified moisture contents compatible with CLT board requirements, the same situation does not exist for hardwoods. Structural grades in the context of this study are those promulgated by the Northeastern Lumber Manufacturers Association (Northeastern Lumber Manufacturers Association [NELMA] 2019).

Hardwood lumber has traditionally been produced to service appearance-graded markets such as furniture, cabinets, moulding, and millwork, etc. Boards are graded, according to the National Hardwood Lumber Association (National Hardwood Lumber Association [NHLA] (2019) rules, based on the amount of defect-free/clear wood. The more clear wood a board contains, the higher value it commands in the marketplace. Further, unlike softwood boards, which are used intact as structural components, hardwood appearance-graded boards are generally not used in their graded form. They are surfaced, ripped, and crosscut into clear wood

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pieces of varying dimensions by the consumers of these boards. These clear pieces are then glued, finger jointed, etc. for the manufacture of furniture, cabinets, millwork, etc.

NHLA graded boards are produced as random width, random length pieces, in a variety of thicknesses, which are categorized in ¼-inch (6.4-mm) increments. A 4/4 board is a nominal 1-inch-thick (2.5-cm-thick) board, and a 5/4 board is a nominal 1.25-inch-thick (3.2-cm-thick) board. Common hardwood lumber thicknesses are 4/4, 5/4, 6/4, 8/4, up to about 16/4, with 4/4 lumber being far and away the most frequently produced thickness (Donnell 2023). It is important to note that CLT manufacturers in Europe routinely utilize 20- to 40-mm-thick (0.78- to 1.56-inch-thick) laminates for panel construction. Thus, from an international perspective, using 4/4 lumber machined to ¾ inch (19.2 mm) is not uncommon (Brandner et al. 2016, Schickhofer et al. 2016).

From a CLT perspective then, what would be the most likely combination of board characteristics that would be the most available and cost effective? Since the marketplace of structural lumber does not include hardwoods, the next best option is to investigate the feasibility of purchasing 4/4, rough, kiln-dried lumber, which is readily available from hardwood lumber producers, and processing it into structural lumber. This approach was taken with the research reported here for red oak (*Quercus rubra*) and soft maple (*Acer saccharinum*). Thus, the overall objectives of this study were as follows:

1. Determine the visual structural grade distribution of the red oak and soft maple boards, and compare the results both overall and by NHLA grade.
2. Determine the modulus of elasticity (MOE) of each red oak and soft maple board and compare the results to the MOE requirements of ANSI/PRG 320 (American Panel Association [APA] 2019).
3. Conduct a total relative worth analysis for red oak and soft maple to estimate the economic value of both visually graded and mechanically graded boards.
4. Conduct a procurement analysis to determine the volume of lumber required for both species, in order to achieve a fixed volume of CLT-ready lumber.
5. Compare the red oak and soft maple results to similar work reported by Azambuja et al. (2021) with yellow-poplar (*Liriodendron tulipifera*) lumber.

Literature review

A number of investigations into the use of hardwoods for structural purposes have been conducted over the years and cover a number of hardwood species. This review of the literature is subdivided into two components: those publications dealing with visual structural grading of hardwood species and those dealing with mechanical property evaluations.

Visual grading evaluations of hardwood species.— Hassler et al. (2022) provides a summary of various research efforts surrounding visual structural grading results and is briefly summarized here. Research at WVU-AHC evaluated the yield of structural lumber of six hardwood species (Pahl et al. 1992, McDonald et al. 1996,) processed from graded railroad switch ties and ungraded mill-run pallet cants as raw material for bridge superstructures. The six species included red oak, white oak, yellow-poplar, soft maple, beech, and hickory. In the case of graded switch ties, 2 by 7-inch boards were sawn. Ungraded mill-run cants were used to produce 2 by 6-inch boards. All resulting boards were visually graded for structural application according to the standard grades for joists and planks (i.e., Select Structural, No. 1, No. 2, and No. 3). Below Grade boards were also tallied to determine the relative yields among species and cant types. Table 1 shows the results of that research for yellow-poplar, soft maple, and red oak.

There was an obvious difference in the yields of graded switch ties and mill-run cants. For mill-run cants of yellow-poplar, soft maple, and red oak, the yield of No. 2 and better boards was 47, 22, and 42 percent, respectively. Alternatively, the yields of No. 2 and better boards for graded switch ties were 89, 56, and 59 percent, respectively, for yellow-poplar, soft maple, and red oak.

A more recent study by Azambuja et al. (2021) investigated structural lumber yields from NHLA low-grade yellow-poplar boards. Boards provided by a cooperating West Virginia hardwood sawmill included lumber in four NHLA grade categories: No. 2A, No. 2B, No. 3A, and No. 3B. The boards were provided as 4/4, rough, kiln-dried. They were then surfaced and ripped to a fixed width of 6.25 inches (15.9 cm). The final dimension for CLT manufacture was 6 inches (15.3 cm) by 0.75 inches (1.9 cm) by 10 feet (3.0 m). Visual structural grading results, based on the original NHLA grade (before processing), are contained in Table 2.

In general, the yield of No. 2 and better from NHLA graded boards was very poor, ranging from 45.6 percent (No. 2B) down to 18.5 percent (No. 3B). In total, only 36.9 percent of the yellow-poplar boards visually graded as No. 2 and better. The difference with this study and the previous study by Pahl et al. (1992) and McDonald et al. (1996) was that the boards produced in Azambuja et al. (2021) were sorted from the processing of flitches through a gang saw as mill-run lumber.

Pahl et al. (1992) and McDonald et al. (1996) also looked at the breakdown of structural grades by NHLA grade across both types of sawn cants (graded switch ties and mill-run pallet cants). Tables 3 through 5 illustrate those results for yellow-poplar, soft maple, and red oak, respectively.

Overall in Table 3, the proportions of No. 2 and better structural yellow-poplar lumber for NHLA No. 2A, No. 2B, No. 3A, and No. 3B were 70.5, 75.1, 53.3, and 27.8 percent, respectively, reflecting the influence of graded switch ties on the yields (61.2 percent of all boards were from graded switch ties) and much greater than the result from Azambuja et al. (2021).

Table 4 illustrates that, for soft maple, the proportions of No. 2 and better structural lumber for NHLA No. 2A, No. 2B, No. 3A, and No. 3B were 49.3, 43.7, 41.9, and 12.5 percent, respectively, with poorer results than yellow-poplar despite the influence of graded switch ties on the yields (62.1 percent of the boards were from graded switch ties).

For red oak, Table 5 illustrates that the proportions of No. 2 and better structural lumber for NHLA No. 2A, No. 2B, No. 3A, and No. 3B were 63.6, 71.4, 63.5, and 53.3 percent, respectively, with better results than soft maple, but somewhat poorer than yellow-poplar. Even with the

Table 1.—Structural lumber yields of yellow-poplar, soft maple, and red oak lumber sawn from graded switch ties and ungraded, mill-run pallet cants.[a]

Species	Cant type	Structural grade (surfaced 4 sides)					Total boards (N)
		Select Structural (%)	No. 1 (%)	No. 2 (%)	No. 3 (%)	Below Grade (%)	
Yellow-poplar	Mill run cant	10	5	32	26	27	152
	Graded switch tie	42	22	25	9	2	240
Soft maple	Mill run cant	3	4	15	28	50	120
	Graded switch tie	16	8	32	33	11	196
Red oak	Mill run cant	5	5	32	43	15	112
	Graded switch tie	5	7	47	32	9	1,088

[a] From Pahl et al. (1992).

influence of graded switch ties on the yields (90.7 percent of the boards were from graded switch ties), red oak results were not able to match the yellow-poplar results.

Faust et al. (1990) studied sweetgum for structural lumber purposes, using yellow-poplar as a control species. Approximately 22 thousand board feet (MBF; 52 m^3) of both species in ungraded sawlogs were investigated, in a combination of both 2 by 4s and 2 by 8s. The logs were sawn into nominal 8 by 8-inch (6.5 cm by 6.5-cm) cants then sawn into 2 by 8s from which 2 by 4s were subsequently sawn. Similarly, Moody et al. (1993) studied structural lumber yields from yellow-poplar logs sourced from southwestern West Virginia. Green et al. (1994) considered discrepancies in both studies and then normalized the results to reflect yields of No. 2 and better structural lumber. For the Faust et al. (1990) study, the No.2 and better sweetgum yields were 71.5 percent for 2 by 4s and 51.1 percent for 2 by 8s. For yellow-poplar, the No. 2 and better yields were 77.5 and 85.9 percent, respectively, for 2 by 4s and 2 by 8s. The normalized results presented by Moody et al. (1993) were 88.3, 90.3, and 91.6 percent, respectively, for 2 by 4s, 2 by 6s, and 2 by 8s.

Janowiak et al. (1995) studied red maple (*Acer rubrum*) for glulam applications. Study logs were sourced from northcentral Pennsylvania sites. Logs were first processed with primary breakdown to recover appearance-grade hardwood lumber. The resulting log hearts (cants from 6 inches [15.2 cm] down to 4.5 inches [11.4 cm]) were processed through a resaw to recover 2 by 4 and 2 by 6 material. Structural grades were determined prior to drying and surfacing and yielded 5.8 percent Select Structural, 24.8 percent No. 1, 40.9 percent No. 2, 19.8 percent No. 3, and 8.7 percent Below Grade material. Following drying and surfacing the lumber was sorted, but no final tally of grade yields was provided.

Kretschmann et al. (1999) studied structural grade yields from 50 hybrid poplar (*Populus*) logs procured from plots in central Wisconsin. The logs were about 9 feet (2.7 m) in length, with scaling diameters from 6.75 to 11.5 inches (17.2 to 29.2 cm), with 2 by 4s being the target product. Results showed that 66 percent of the 2 by 4s were No.2 and better, with 86 percent of the 2 by 4s being No. 3 and better grade.

Two studies investigated the impact of log grade on the production of structural lumber. Log grades were based on the standard US Department of Agriculture (USDA) Forest Service log grades F1, F2, F3, and construction grades. The logs were all 10 feet (3.0 m) in length, with a minimum scaling diameter of 10 inches (25.4 cm). The sawing pattern included a 4-inch (10.2-cm) heart centered cant and at least two 7/4 flitches on each side of the cant, which were then sawn into 2 by 4s, dried, surfaced, and structurally graded. In the first study by McDonald and Whipple (1992), red oak logs in log grades F2, F3, and construction grades (it was assumed that F1 logs would be utilized in a different manner than the poorer quality logs) were analyzed. The structural yields for the F2 log grade were 33 percent No. 2 and better and 51 percent for No. 3 and better; for the F3 log grade 16 percent No. 2 and better, and 26 percent No. 3 and better; and for the construction grade 39 percent No. 2 and better and 53 percent No. 3 and better. The unaccounted for yields were in Economy grade 2 by 4s.

Table 2.—Yield of structural-grade lumber from yellow-poplar lumber processed (surfaced four sides) from 4/4, rough, kiln-dried boards, by NHLA lumber grade.[a,b,c]

NHLA grade	NELMA grade No. of boards (%)					Total boards (N)
	SS	No. 1	No. 2	No. 3	BG	
2A	75 (17.0)	31 (7.0)	88 (20.0)	90 (20.4)	157 (35.6)	441
2B	15 (8.9)	18 (10.7)	44 (26.0)	35 (20.7)	57 (33.7)	169
3A	41 (11.6)	24 (6.8)	62 (17.5)	58 (16.4)	169 (47.7)	354
3B	7 (3.1)	7 (3.1)	28 (12.3)	28 (12.3)	158 (69.2)	228
Total	138 (11.6)	80 (6.7)	222 (18.6)	211 (17.7)	541 (45.4)	1,192

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.
[b] From Azambuja et al. (2021).
[c] No visual override was applied to the boards; they were analyzed as mill run lumber.

Table 3.—Yellow-poplar structural yields by NHLA grade (2A, 2B, 3A, and 3B) from all cant types.[a,b]

NHLA grade	NELMA grade (%)					Total boards (N)
	SS	No. 1	No. 2	No. 3	BG	
2A	44.3	8.2	18.0	21.3	8.2	61
2B	19.2	19.2	36.7	14.4	10.5	229
3A	0.0	20.0	33.3	26.7	20.0	15
3B	0.0	0.0	27.8	33.3	38.9	18

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.
[b] From Pahl et al. (1992).

Table 5.—Red oak structural yields by NHLA grade (2A, 2B, 3A, and 3B) from all cant types.[a,b]

NHLA grade	NELMA grade (%)					Total boards (N)
	SS	No. 1	No. 2	No. 3	BG	
2A	13.3	11.9	38.4	23.8	12.6	151
2B	4.7	14.1	52.6	20.8	7.8	192
3A	4.1	8.2	51.2	26.5	10.0	170
3B	1.0	3.2	49.1	38.5	8.2	587

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.
[b] From Pahl et al. (1992).

In the second study by McDonald et al. (1993), red maple logs were examined based on USDA Forest Service standard grades F1, F2, and F3. The 100 logs procured in Vermont for the study were treated similarly to the logs in the red oak study above. The F1 grade logs yielded 55 and 73 percent in No.2 and better and No. 3 and better, respectively. The F2 logs yielded 27 and 43 percent in No. 2 and better and No. 3 and better, respectively. The F3 logs yielded 19 and 37 percent in No. 2 and better and No. 3 and better, respectively. Again, the unaccounted for percentages were in Economy grade 2 by 4s.

Mechanical property evaluations of hardwood species.—Some previous research has been conducted comparing machine stress rating (MSR) of hardwoods to visual grading results, illustrating the potential for better yield results than visual grading. Hassler et al. (2022) summarized this work, which is replicated, in part, here.

Green et al. (1994) performed both MSR and visual grading of 803, 2 by 8 mixed oak boards. The lumber was sawn from graded switch ties, then dried to an average moisture content of 17 percent and surfaced on two faces. Structural grade yields from visual grading showed 61 percent of the lumber was No. 3 visual grade, 35 percent was No. 2 grade, 3 percent was No. 1 grade and only about 1 percent was Select Structural. Results showed that while only 1 percent of the lumber qualified as Select Structural by visual grading, 36 percent of it could be assigned an MSR grade with properties equal to or greater than those of Select Structural (Green et al. 1994). The authors further concluded that, using MSR techniques, it is possible to achieve grades of lumber not attainable using visual grading standards.

Another study, unpublished by Green, Wolcott, and Hassler (Senalik and Green 2020, pp. 35–36), compared visual grading and MSR grading of 2 by 6 lumber sawn from log heart cants for several hardwood species. These were the same boards produced in the Pahl et al. (1992) study. Results showed that MSR ratings of these boards were 10 to 20 percent higher than visually graded properties. "Thus, research to date indicates the possibility of achieving higher yields for a specified set of allowable properties using the MSR process" (Senalik and Green 2020).

Table 4.—Soft maple structural yields by NHLA grade (2A, 2B, 3A, and 3B) from all cant types.[a,b]

NHLA grade	NELMA grade (%)					Total boards (N)
	SS	No. 1	No. 2	No. 3	BG	
2A	19.5	9.1	20.7	22.1	28.6	77
2B	3.7	7.4	32.6	34.8	21.5	135
3A	3.2	12.9	25.8	48.4	9.7	31
3B	0.0	0.0	12.5	50.0	37.5	24

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.
[b] From Pahl et al. (1992).

More recent research conducted at WVU-AHC with yellow-poplar for production of CLT showed similar results to these earlier studies. Azambuja et al. (2021) subjected 1,135 yellow-poplar visually graded boards to nondestructive proof-loading to determine their MOE. The minimum MOE required for boards used to produce CLT panels is 1.20 by 10^6 psi (8.3 KPa), a figure chosen to determine what proportion of the boards could meet the minimum MOE specifications required for boards used in CLT panels (APA 2019). Table 6 summarizes those results. A total of 39 boards (3.4 percent) out of the 1,135 boards tested did not meet the MOE threshold specifications, which implies that MSR may ultimately be the better alternative for evaluating hardwood boards for CLT production. It is important to remember that these boards were mill run, so that there was no visual override to remove boards from the sample prior to testing.

Materials and Methods

This study focused on samples of NHLA low-grade red oak and soft maple lumber typically used for industrial applications such as wooden pallets and crates and flooring applications, among others. Approximately 4 MBF (9.5 m^3) of 4/4 rough cut, kiln-dried red oak and 4 MBF (9.5 m^3) of 4/4, rough cut, kiln-dried soft maple was procured from a cooperating mill in northern West Virginia. In both species,

Table 6.—Bending modulus of elasticity (MOE_b) analysis of yellow-poplar boards grouped by visual structural grades (Azambuja et al. 2021).[a]

Visual grade ≥	Select Structural	No. 1	No. 2	No. 3	Below Grade
Total boards (N)	137	80	221	207	490
No. of boards $<1.20 \times 10^6$ psi[a]	1	1	4	4	29

[a] The minimum MOE required for boards used in the production of cross-laminated timber panels is 1.20×10^6 psi (1.4 KPa), based on data published in the American Panel Association PRG-320 (APA 2019).

there were two market categories: flooring and 7-inch-wide pallet boards. The boards were sawn from 7.25-inch-thick (18.4-cm-thick) flitches. This is the mill's standard process for sawing a combination of grade lumber and pallet boards: saw logs to a 7.25-inch (18.4-cm) flitch, then process the flitch through a gang saw. The higher-grade boards (NHLA grades 1 Common and better) are sorted for appearance markets, while the remaining lower grade boards (2A, 2B, 3A, and 3B) are ordinarily sorted out for pallet boards. Further, the mill sorted out the 10-foot (3.0-m) boards that were requested by WVU-AHC for the CLT research. Also, the boards were effectively mill run, with no visual override applied.

The boards were kiln-dried to a moisture content between 6 and 8 percent before delivery, which is not a common treatment for low-grade hardwood lumber. The flooring was provided as random width and length lumber in NHLA grades 2A Common, 3A Common, and 3B Common, while the 7-inch (17.8-cm) pallet lumber was provided in a range of grades: No. 2A, No. 2B, No. 3A, and No. 3B Common. Boards that did not meet a minimum width of 6.5 inches (16.5 cm) were removed from the study population. The sample population for red oak was 544 boards (296 pallet boards and 248 flooring boards). The sample population for soft maple was 599 boards (507 pallet boards and 92 flooring boards). All boards were sequentially numbered on both ends.

Two graders, a structural grader contracted from Timber Products Inspection, Inc. and an NHLA grader from the cooperating sawmill, visually graded the sample population boards in the rough condition. Boards were graded for NELMA structural grade and NHLA appearance grades (Fig. 1 summarizes the visual grading methods).

Following the initial grading, the boards were surfaced on both wide faces to an approximate thickness of 0.95 inches (2.4 cm) at the cooperating mill. After surfacing, the lumber was transported to the WVU Wood Science research laboratories to be ripped to a target width of 6.25 inches (15.9 cm), with a final average width of 6.17 inches (15.7 cm).

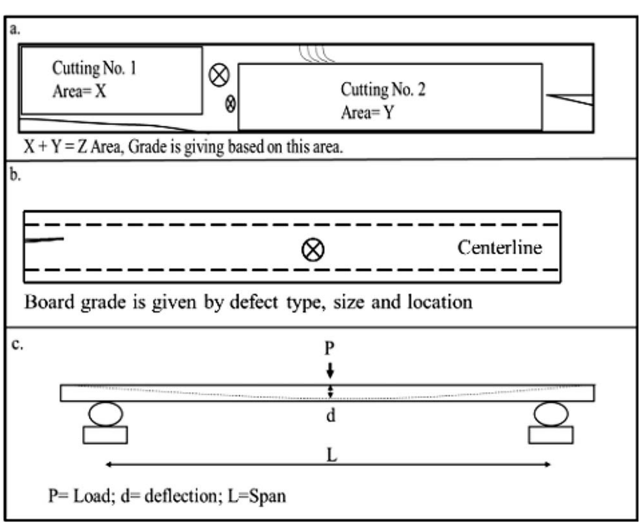

Figure 1.—Illustration of the different grading options used in this research. (a) National Hardwood Lumber Association visual grade, (b) Northeastern Lumber Manufacturers Association visual grade, (c) Nondestructive center point proof loading test (Azambuja et al. 2021).

The ripping was conducted with the goal to maximize the defect-free area on each board, while simultaneously reducing waste. Following processing (–surfaced on four sides), the lumber was regraded according to NELMA and NHLA rules by the same inspectors who conducted the initial grading.

The distribution of the structural grades following processing, by NHLA grades before processing, for both species, were analyzed as r by c contingency tables using the χ^2test statistic with a confidence level of $\alpha = 0.05$ (Conover 1980).

In order to draw comparisons between visual grading and mechanical properties, each of the boards underwent nondestructive center-point bending tests to determine the flatwise bending MOE. The boards were tested in a flatwise orientation to closely mimic the bending forces of a board being encountered as a CLT floor or wall panel component (Fig. 1c). MOE was calculated using deflection and load data using the American Society for Testing and Materials (ASTM) center-point test (ASTM D198-15; ASTM 2015). Each board was subjected to 3 inches (7.6 cm) of deflection using a center-point load configuration and the applied force and deflection values were recorded. The 10-foot (3.0-m) boards were tested over a span of 114 inches (289.6 cm) and the 9-foot (2.7-m) boards were tested over a span of 100 inches (254.0 cm). Equation 1 was used to calculate MOE for each board:

$$\text{MOE}_s = \frac{M \times L^3}{48 \times I} \quad (1)$$

where:

MOE_s = the modulus of elasticity in bending flatwise (lb/in^2),
M = the slope of the load deflection curve (lb/in),
I = the moment of inertia (in),
L = board length (in).

Once the bending data were collected, the boards were measured to determine the thickness and width where the load was being applied. Measurements to determine this profile were taken 63 inches (160.0 cm) from the end of each 10-foot (3.0-m) board and 53 inches (134.6 cm) from the end of each 9-foot (2.7-m) board. MOE values were calculated using the results of the bending and deflection tests.

The data sets were then analyzed to obtain descriptive statistics (mean, standard deviation, etc.) for each species. The boards were grouped by structural grade and tested for normality using the Shapiro-Wilk W test. The null hypothesis was that data are normally distributed. Small P values lead to the rejection of the null hypothesis and therefore mean that the data are not normally distributed. A probability level of $\alpha = 0.05$ was used for the analysis.

The nonparametric Steel-Dwass test was performed on the NELMA grades (Select Structural, No. 1, No. 2, No. 3, and Below Grade), within their respective species, to determine if the average MOE values between grades were significantly different from one another, again using a significance criteria of $\alpha = 0.05$. The null hypothesis in this test is that the populations are not statistically different. Nonparametric statistics were used in this study because not all the individual structural grades were normally distributed. All statistical tests utilized JMP (2015) as the statistical analysis software.

To evaluate the value or worth of NHLA graded lumber being processed into structurally graded lumber, an approach described as the total relative worth analysis developed by Pahl et al. (1992) was used in this study. Relative worth of the lumber is determined using market prices by grade (NHLA) with the frequency of occurrence of structural grades from the NHLA graded lumber, and the relative strength ratio of each structural grade. This approach was taken because a publicly available pricing structure does not exist for structurally graded hardwood lumber. Since market prices for commodity products like pallets and flooring usually focus on green lumber (with the exception of NHLA No. 2A lumber), a cooperating sawmill was contacted to obtain estimates of green lumber prices per MBF as well as kiln-drying costs for red oak and soft maple of lower grade hardwoods.

Relative strength ratios were the same as those reported in Azambuja et al. (2021) and were 0.66, 0.60, 0.49, 0.30, and 0.0 for structural grades Select Structural, No. 1, No. 2, No. 3, and Below Grade, respectively. These relative strength values were extracted from ASTM D245-06 (ASTM 2019), which provides strength reducing correction factors for defect-free, straight-grained lumber.

Using a frequency table of NHLA grades, by NELMA grades, relative strength ratios, and relative pricing, Equation 2 was used to determine relative worth. The relative worth by species was determined by applying Equation 2 to each NHLA grade.

$$\text{TRW} = \sum_{SS}^{BG} \frac{\text{Cell frequency}}{\text{Row frequency}} \times \frac{\text{Relative strength}}{\text{Relative price}} \times 1{,}000 \quad (2)$$

where:

TRW = total relative worth
BG = Below Grade
SS = Select Structural.

A second total relative worth analysis was conducted, focusing on NHLA grade frequencies and their associated MOE values. There are no relative strength correction factors for MSR rated lumber. Since no strength ratios are available for proof loading applications, the relative strength ranges used in this analysis are the same ones used by Azambuja et al. (2021), to allow for comparison with those yellow-poplar results. The current pricing according to NHLA grade was the same as those used in the relative worth analysis of visually graded lumber.

In addition to the total relative worth analysis, a yield analysis was completed to better illustrate the volumes of each rough cut NHLA lumber grade that would have to be procured to create 1,000 feet^2 of surface measure of CLT-ready lumber. These values are reported as ratios of purchased material to 1,000 feet^2 of surface measure in CLT-ready boards. From a CLT procurement perspective, the basic approach is to determine how many 4/4, rough, kiln-dried boards are required to yield 1,000 ft^2 (surface measure) of CLT-ready boards.

Results

Visual grading results

The sample population of red oak contained 544 boards and the sample population of soft maple boards contained 599 boards. The pallet stock and flooring samples were combined for analysis purposes.

Red oak visual grading results.—Table 7 illustrates the breakdown of NELMA grades for the 544 red oak boards, both before and after processing. Significant gains were made in the No. 2 and better NELMA structural grades following surfacing. These increases included a 341 percent increase in Select Structural, a 160 percent increase in No. 1 and a 10.1 percent increase in No. 2. Importantly, No. 2 and better boards increased in number from 116 to 190, a 64 percent increase. These increases in the percentage of higher structural grades resulted in accompanying decreases in the volume of No. 3 and Below Grade boards, indicating that surfacing dramatically improved the structural grade distribution. A χ^2 test comparing the distribution of NELMA grades for red oak before and after the treatment showed that the difference between distributions to be significant ($P < 0.0001$).

From a CLT procurement perspective, the more important question is this: What did the initial distribution of NHLA graded boards (preprocessing) yield with respect to NELMA grades following processing? Table 8 provides a breakdown of these pre- and postprocessing distributions for red oak.

A χ^2 test of this 3 by 5 contingency table resulted in a nonsignificant result ($P = 0.21$) indicating that there was no statistical difference between the NHLA grades and the resulting NELMA distributions. Of importance to CLT manufacturing is the proportion of No. 2 and better boards. For the red oak sample, the proportions were 38.0, 33.3, and 33.9 percent respectively, for No. 2A, No. 3A, and No. 3B. Since this result was unexpected, the authors believe part of the reason was that many of the boards had iron oxidation on the surface that made accurate preprocessing NHLA grading difficult, which could have contributed to this unexpected increase in yield for these grades.

Soft maple visual grading results.—As with red oak, there was an improvement in the grade distribution for soft maple (Table 9). Although there was a reduction in No.1 boards, the overall improvement in No. 2 and better boards was 55.9 percent, with an increase in Select Structural of over 2000 percent. A χ^2 test comparing the distribution of NELMA grades for before and after processing showed that the difference between distributions to be significant ($P < 0.0001$).

The comparison of preprocessed NHLA graded boards, by grade, for soft maple, and processed NELMA graded boards is presented in Table 10. A χ^2 test of the 4 by 5 contingency table resulted in a significant test result ($P < 0.00001$), indicating that there is a statistical difference between the NHLA grades and the NELMA distributions. Again, the proportion of No. 2 and better structurally graded boards is of importance for CLT manufacturing. The percentages of No. 2 and better were 58.3, 58.2, 45.4, and 33.8 percent, respectively, for No. 2A, No. 2B, No. 3A, and No. 3B.

Table 7.—Comparison of pre- and postprocessing Northeastern Lumber Manufacturers Association grade distributions for red oak.

No. of boards by grade	Select Structural	No. 1	No. 2	No. 3	Below Grade
Preprocessing	12	15	89	76	352
Postprocessing	53	39	98	55	299

Table 8.—Comparison of preprocessed NHLA graded red oak boards with the NELMA grade distributions of those boards after processing.[a]

NHLA grades preprocessing			Postprocessing NELMA grades									
			SS		No. 1		No. 2		No. 3		BG	
	n	%	n	%	n	%	n	%	n	%	n	%
2A	163	100.0	18	11.0	12	7.4	32	19.6	20	12.3	81	49.7
3A	150	100.0	11	7.3	12	8.0	27	18.0	21	14.0	79	52.7
3B	231	100.0	24	10.4	15	6.5	39	16.9	14	6.1	139	60.1
Total	544	100.0	53	9.7	39	7.2	98	18.0	55	10.1	299	55.0

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.

Table 9.—Comparison of pre- and postprocessing Northeastern Lumber Manufacturers Association grade distributions for soft maple.

No. of boards by grade	Select Structural	No. 1	No. 2	No. 3	Below Grade
Preprocessing	5	66	99	65	364
Postprocessing	109	48	108	61	273

Azambuja et al. (2021) presented a similar summary of preprocessed NHLA grades and the resulting distribution of NELMA grades for yellow-poplar. This data are presented in Table 11 as a 4 by 5 contingency table. The χ^2 test resulted in a statistically significant test result ($P < 0.00001$), indicating that the NELMA processed grades were different from the NHLA preprocessed grades. The percentages of No. 2 and better were 44.0, 45.6, 35.9, 18.5 percent, respectively, for No. 2A, No. 2B, No. 3A, and No. 3B. In both soft maple and yellow-poplar the NHLA No. 2A and No. 2B outperformed No. 3A and 3B grades.

MOE results

Both study populations of red oak and soft maple underwent nondestructive evaluation (NDE) at WVU labs to determine the MOE of each board in the sample populations. APA PRG-320 (APA 2019) suggests a minimum MOE value for CLT panels of 1.2 by 10^6 psi (8.3 KPa) (for the longitudinal layers) based on E1 layup standards. Given the large volume of lumber graded out as Below Grade in both red oak (55.0 percent) and soft maple (45.6 percent), there is justification to explore whether nondestructive testing can improve the yield of CLT ready boards versus visual grading of those boards.

Red oak MOE analysis results.—The red oak MOE distribution and associated statistics are provided in Figure 2 and Table 12. Of the 544 red oak boards tested, only 22 boards (4.0 percent) did not meet ANSI/APA PRG-320 minimum MOE requirements (Table 12). Three of these boards broke during the MOE testing and were recorded as having an MOE of 0 psi (0 KPa). The average MOE value calculated for red oak was 1.80 by 10^6 (12.4 KPa), ranging from 0 to 2.90 by 10^6 psi (0 to 20 KPa). Skewness for this distribution was limited (−0.89) and kurtosis was 4.1. This large kurtosis value indicates that the distribution has outliers that affected the distribution.

The Shapiro-Wilk test for normality showed the MOE distribution of red oak to be nonnormal (W = 0.048), $P < 0.0001$; Fig. 2). There were outliers in Grade No. 2 that were significantly higher than the average MOE value. Outliers observed in Below Grade were from boards that broke during the MOE bending test. Analysis of the individual structural grade distributions were completed with the Kruskall-Wallis and Steel-Dwass nonparametric tests (JMP 2015).

The Kruskal-Wallis test of MOE, by structural grades, showed a significant result ($P < 0.0001$) indicating differences between grades. The Steel-Dwass test was then used to determine which pairs of grades were significantly different from one another. Those differences included No. 3 and Select Structural ($P = 0.0346$), Below Grade and No.2 ($P = 0.0013$), as well as Below Grade and Select Structural ($P < 0.0001$).

Table 10.—Comparison of preprocessed NHLA soft maple graded boards with the NELMA grade distributions of those boards after processing.[a]

NHLA Grades preprocessing	Totals		Postprocessing NELMA grades									
			SS		No. 1		No. 2		No. 3		BG	
	n	%	n	%	n	%	n	%	n	%	n	%
2A	60	100.0	15	25.0	3	5.0	17	28.3	4	6.7	21	35.0
2B	122	100.0	40	32.8	12	9.8	19	15.6	10	8.2	41	33.6
3A	154	100.0	21	13.6	18	11.7	31	20.1	19	12.4	65	42.2
3B	263	100.0	33	12.5	15	5.7	41	15.6	28	10.6	146	55.6
Total	599	100.0	109	18.2	48	8.0	108	18.0	61	10.2	273	45.6

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade.

Table 11.—A comparison of preprocessed NHLA graded boards with the NELMA grade distributions of those boards in the processed form for yellow-poplar.[a,b]

NHLA grades preprocessing	Totals		Postprocessing NELMA grades									
			SS		No. 1		No. 2		No. 3		BG	
	n	%	n	%	n	%	n	%	n	%	n	%
2A	441	100.0	75	17.0	31	7.0	88	20.0	90	20.4	157	35.6
2B	169	100.0	15	8.9	18	10.7	44	26.0	35	20.7	57	33.7
3A	354	100.0	41	11.6	24	6.8	62	17.5	58	16.4	169	47.7
3B	228	100.0	7	3.1	7	3.1	28	12.3	28	12.3	158	69.2
Total	1,192	100.0	138	11.6	80	6.7	222	18.6	211	17.7	541	45.4

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association.
[b] From Azambuja (2021).

Soft maple MOE analysis results.—The soft maple MOE distribution and associated statistics are provided in Figure 3 and Table 13.

Of the 599 soft maple boards tested, 18 boards (3.0 percent) measured less than 1.2 by 106 psi (8.3 KPa) and failed to meet the requirements in ANSI/APA PRG-320 (APA 2019) for longitudinal laminates. The average MOE value for soft maple was 1.7 by 10^6 (11.7 KPa). The maximum MOE recorded was 2.9 by 10^6 psi (20.0 KPa) and the minimum was 0 psi (0 KPa). The Shapiro-Wilk test for normality showed the MOE distribution of soft maple to be nonnormal ($W = 0.983$, $P < 0.0001$).

Table 13 shows the MOE results by NELMA visual grades and the number of boards that did not meet the minimum MOE in CLT layup E1. The Steel-Dwass test of individual grades showed significant differences between Below Grade and all the other grades (Select Structural ($P < 0.0001$), No. 1 ($P < 0.03$), No. 2 ($P < 0.0001$), and No. 3 ($P < 0.0001$)).

Total relative worth analysis of red oak and soft maple

The foregoing statistical analysis of visual and mechanical grading provides valuable insight into the technical feasibility of utilizing red oak and soft maple for CLT manufacturing. The total relative worth analysis was conducted in an attempt to provide further insight into the economic feasibility of both species.

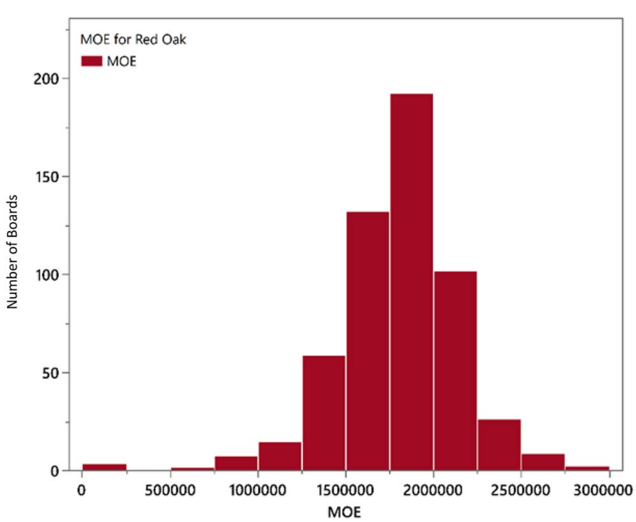

Figure 2.—Modulus of elasticity (MOE)histogram for red oak.

Relative worth for visually graded red oak and soft maple.—Ideally the relative worth of hardwood structural lumber would be the market price for each structural grade. Unfortunately, a hardwood structural lumber market with accompanying price reports (similar to the third-party pricing reports available for appearance-graded hardwood lumber) has yet to be developed, as there has not been a viable market for structural hardwoods. Thus, determining a relative worth for hardwood structural lumber is more challenging, but necessary in considering the economic feasibility of producing NHLA graded hardwood to be used in structural applications. The prices for kiln-dried No. 2A red oak and soft maple were taken from the Hardwood Market Report (February 2023). For grades No. 2B and lower, a cooperating sawmill provided the green selling price and the cost to kiln dry this lumber, which are combined in Tables 14 and 15 for red oak and soft maple, respectively.

The top portion of Table 14 is a 3 by 5 contingency table that describes the frequency of red oak boards by NHLA and NELMA grades. The second half of that table provides the relative worth of each NHLA grade for each NELMA grade (calculated from Eq. 2). The value in the last column describes the total relative worth for the corresponding NHLA grade, with the weighted total being the relative worth over all grades of red oak, in this instance. Conceptually, the output value is a representative measure of relative strength that each NHLA grade yields per dollar of input costs. In the case of No. 2A and Select Structural there are 18 boards; this frequency is then divided by the total number of No. 2A boards, which is 163. The product of this is then multiplied by the product of relative strength ratio (0.66) divided by relative value (US$) and that product is multiplied by 1,000. The resulting value equals 0.108 rounded to the nearest thousandth. The results from Table 14 indicate that NHLA grade No. 3B has the highest relative worth for red oak (0.521). This is followed by No. 3A (0.453) and No. 2A (0.371) and a weighted total relative worth of 0.457.

Table 15 presents the relative worth results for visually graded soft maple. Grade No. 2B had the highest total relative worth totaling 0.941. This is followed by No. 3A

Table 12.—Red oak MOE results by NELMA grade and overall.[a]

Descriptive statistics	Overall	SS	No. 1	No. 2	No. 3	BG
Count	544	53	39	98	55	299
Mean (Mpsi)	1.80	1.99	1.86	1.89	1.84	1.73
Minimum (Mpsi)	0	1.47	2.1	1.27	1.09	0
Maximum (Mpsi)	2.90	2.55	2.49	2.89	2.58	2.90
Median (Mpsi)	1.82	1.95	1.88	1.89	1.84	1.76
SD (Mpsi)	0.344	0.27	0.28	0.26	0.27	0.38
Kurtosis	4.0995	−0.3906	0.7247	2.1753	0.9283	3.8716
Skewness	−0.8940	0.2144	−0.3271	0.5318	0.1595	−1.0291
No. below 1.2×10^6 psi	22	0	0	0	1	21
Shapiro-Wilkes probability < W	<0.0001	0.4057	0.1059	0.0082	0.726	<0.0001

[a] NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade; Mpsi = megapound per square inch.

(0.740), No. 3B (0.564), and No. 2A (0.411) and a weighted total relative worth of 0.670. Thus, on a weighted total relative worth basis, soft maple is a better choice than red oak for CLT production.

Relative worth analysis of non-destructively (MOE) graded red oak and soft maple.—Tables 16 (red oak) and 17 (soft maple) present an MOE based analysis of relative worth. This analysis uses the distribution of MOE values presented in Azambuja et al. (2021) for yellow-poplar in order to make relative worth comparisons among the three species and is predicated on the minimum CLT panel requirements of 1.2 by 10^6 psi (8.3 KPa).

Red oak grade No. 3B, in Table 16, has the highest relative worth (2.034), followed by No. 3A (1.596) and No. 2A (1.191), a similar ordering to the visual grading total relative worth results. Table 17 shows grade No. 2B of soft maple had the highest relative worth (1.456), followed by No. 3A (1.166), No. 3B (0.894), and No. 2A (0.637), a similar ordering to the visual grading relative to total relative worth results. However, this analysis shows that total weighted relative worth for red oak species (1.661) surpasses that of soft maple as a species (1.053).

In comparing the results of relative worth for visual grading and for nondestructive testing, the best performing NHLA grade for red oak was No. 3B for both methods of grading. For soft maple NHLA No. 2B was the best performing grade for both methods of grading. It is important to remember that relative worth will change as prices change, with relative worth increasing as prices decrease. The best performing grade can change depending on the relative impact of price changes between grades.

However, for both red oak and soft maple, the relative price change required to move the top performing grade to the second highest performing grade would be significant. For visually graded red oak, the price of No. 3B would have to increase by US$60 per MBF (US$25.40 per m^3) for visually graded lumber and US$110 per MBF (US $46.60 per m^3) for mechanically graded lumber. Similarly, the soft maple price for No. 2B would have to increase US$109 per MBF (US$46.19 per m^3) for visual

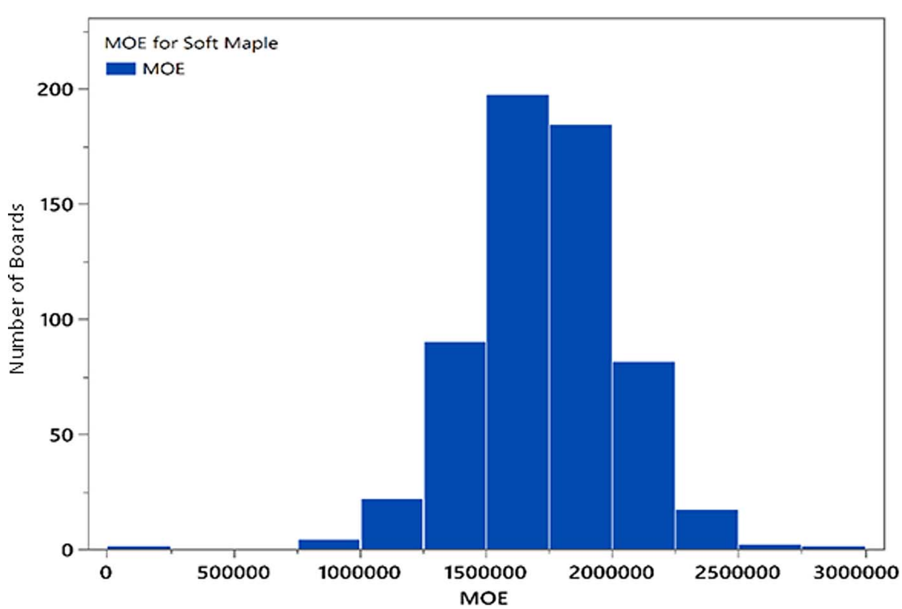

Figure 3.—Modulus of elasticity (MOE) histogram for soft maple.

Table 13.—Soft maple descriptive statistics based by NELMA grade and overall.

Descriptive statistics	Overall	SS	No. 1	No. 2	No. 3	BG
Count	599	109	48	108	61	273
Mean (Mpsi)	1.73	1.85	1.76	1.79	1.82	1.63
Minimum (Mpsi)	0	1.33	1.30	1.25	1.32	0
Maximum (Mpsi)	2.86	2.86	2.20	2.55	2.28	2.38
Median (Mpsi)	1.73	1.83	1.76	1.79	1.82	1.63
SD (Mpsi)	0.29	0.28	0.22	0.24	0.22	0.31
Kurtosis	2.1570	0.9245	−0.2883	0.9658	−0.7079	2.1177
Skewness	−0.3222	0.6915	−0.0910	0.5914	−0.1271	−0.5910
Below 1.2×10^6 psi	18	0	0	0	0	18
Shapiro-Wilks probability <W	<0.0001	0.4057	0.1059	0.0082	0.726	<0.0001

[a] NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade; Mpsi = megapound per square inch.

graded lumber and US$99 per MBF (US$41.95 per m^3) for MSR rated lumber, respectively. In both cases, the likelihood that prices would increase to these levels is somewhat problematic.

Procurement issues.—When considering procuring 4/4, rough, kiln-dried boards the question is how many board feet are required to yield 1,000 feet^2 (92.9 m^2; surface measure) of CLT-ready boards. Taking the No. 2A NHLA graded red oak boards, for instance, 163 boards yielded 62 boards of No. 2 and better, or 310 feet^2 (28.8 m^2) of surface measure (each finished board has 5 ft^2 [0.46 m^2] of surface measure at 6 in [15.2 cm] wide by 10 ft [3.1 m] in length). Solving for 1,000 feet^2 (92.9 m^2) of surface measure for CLT-ready boards requires 526, 4/4, rough, kiln-dried boards. The 4/4, rough, kiln-dried boards in this study contain 6 board feet (0.014 m^3), so it would require 3.16 MBF (7.5 m^3) of 4/4, rough, kiln-dried boards to yield 1,000 feet^2 (92.9 m^2) of surface measure of finished boards.

Table 18 summarizes the volume of 4/4, rough, kiln-dried red oak and soft maple required to yield 1,000 feet^2 (92.9 m^2) of surface measure in CLT-ready boards. Because of the low yield of visually graded structural lumber, procuring 1,000 feet^2 (92.9 m^2) of surface measure of CLT-ready boards from 4/4, rough, kiln-dried boards will incur a substantial cost. Overall, from a purely procurement perspective, soft maple is a more economically feasible alternative than red oak for purchasing CLT-destined lumber.

Discussion

The results of this study, combined with the results of the yellow-poplar study reported by Azambuja et al. (2021), confirm the challenges in utilizing hardwood lumber in CLT manufacturing, as discussed by Hassler et al. (2022). Focusing on the most commonly available form of hardwood lumber—4/4, rough, kiln dried—it becomes evident that difficulties exist in creating CLT-ready hardwood lumber.

Each step involved in creating CLT ready lumber, as detailed in this study, holds its own challenges. Previous research by the several authors reported here shows wide discrepancies in the yield of No. 2 and better boards from a variety of species when utilizing visual grading. This discrepancy can, in part, be explained by the varying forms of graded railroad switch ties/ungraded pallet cants/flitches that served as the source of structural lumber in these various studies.

While 4/4, rough, kiln-dried lumber is readily available in the marketplace, there is variability in the form of that lumber. That is, the cooperating mill in this study was set up to saw 7.25-inch (18.4-cm) boards from a flitch in order to service pallet lumber markets. For a level of compatibility with softwood markets utilizing nominal 6-inch-wide lumber, this becomes an issue. It is unlikely that the cooperating mill would see an advantage to sawing a 6-inch (15.2-cm) flitch, as it would negatively impact the production of first- and second-grade lumber.

Table 14.—Relative worth of 4/4, rough, kiln-dried NHLA grade red oak lumber according to price, frequency, and percentage of clear strength, by NELMA visual grade.[a]

NELMA grade≥		SS	No. 1	No. 2	No. 3	BG	Total
				Relative strength ratio			
NHLA grade	US$/MBF	0.66	0.6	0.49	0.3	0	
2A	675	18	12	32	20	81	163
3A	500	11	12	27	21	79	150
3B	400	24	15	39	14	139	231
NHLA grade				Relative worth			
2A	675	0.108	0.065	0.143	0.055	0.00	0.371
3A	500	0.097	0.096	0.176	0.084	0.00	0.453
3B	400	0.171	0.097	0.207	0.046	0.00	0.521
						Weighted total	0.457

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade; MBF = 1,000 board feet.

Table 15.—Relative worth of 4/4, rough, kiln-dried NHLA grade soft maple lumber according to price, frequency, and percentage of clear strength, by NELMA visual grade.[a]

		SS	No. 1	No. 2	No. 3	BG	Total
		Relative strength ratio to grade ratio					
NHLA grade	US$/MBF	0.66	0.6	0.49	0.3	0	
2A	860	15	3	17	4	21	60
2B	470	40	12	19	10	41	122
3A	470	21	18	31	19	65	154
3B	470	33	15	41	28	146	263
Total		109	48	108	61	273	599
NHLA grade		Relative worth					
2A	860	0.192	0.035	0.161	0.023	0.00	0.411
2B	400	0.541	0.148	0.191	0.061	0.00	0.941
3A	400	0.225	0.175	0.247	0.093	0.00	0.740
3B	400	0.207	0.086	0.191	0.080	0.00	0.564
					Weighted total		0.670

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade; MBF = 1,000 board feet.

Further, the cooperating mill had to sort out 10-foot (3.0-m) lumber to meet the specification provided by WVU-AHC.

The production of flooring lumber by the cooperating mill further complicated the situation, as boards were random width, ranging from about 3 to 12 inches (7.6 to 30.5 cm). This required a level of sorting to obtain boards that could be processed into CLT-ready boards. Mixing pallet and flooring boards does not create a favorable situation for processing boards.

The next step in the process was to surface the 4/4, rough, kiln-dried boards into boards with CLT board dimensions. This step required surfacing the wide faces through a planer, followed by ripping to the required width. Both of these steps add additional cost to production. While the results of processing showed dramatic improvement of the structural grade distribution, it is not clear that this result offsets the cost of ripping or the loss of volume from the unmarketable pieces that were removed by ripping.

Structural grade distributions of the processed hardwood boards, via visual grading, resulted in poor yields of No. 2 and better structurally graded boards. In the case of red oak, all three NHLA grades produced less than 40 percent No. 2 and better boards. Soft maple was better in that slightly over 58 percent of NHLA No. 2A Common and No. 2B Common graded No. 2 and better structural. The yellow-poplar results from Azambuja et al. (2021) were better than red oak, but much poorer than soft maple, with 44.0 and 45.6 percent No. 2 and better structural for NHLA No. 2A Common and No. 2B Common, respectively.

From a procurement perspective, anywhere from 2.06 MBF (soft maple NHLA No. 2A and No. 2B) to 3.60 MBF (4.9 to 8.5 m^3; red oak NHLA No. 3A) of 4/4, rough, kiln-dried lumber would be required to achieve 1,000 $feet^2$ (92.9 m^2) of surface measure CLT-ready lumber. Table 19 illustrates the volume of 4/4, rough, kiln-dried yellow-poplar lumber required to achieve CLT-ready lumber (Azambuja 2021), which is better than red oak but not as good as soft maple. From a procurement perspective, soft maple appears to be the better choice for visual graded structural lumber.

The nondestructive test results were much more promising than the visual grading results. Given the minimum

Table 16.—Relative worth using the relative strength to grade ratio by MOE range for red oak.[a]

		MOE distribution ($\times 10^6$)					
		>2.0	1.8–2.0	1.5–1.8	1.2–1.5	<1.2	Total
	Value	Relative strength to grade ratio					
NHLA grade	US$/MBF	1	0.9	0.75	0.6	0	
No. 2A	675	41	40	56	20	6	163
No. 3A	500	33	42	50	19	6	150
No. 3B	400	63	65	71	22	10	231
Total		137	147	177	61	22	544
NHLA grade	US$/MBF	Relative worth by grade					
No. 2A	675	0.373	0.327	0.382	0.109	0.03	1.191
No. 3A	500	0.440	0.504	0.500	0.152	0.00	1.596
No. 3B	400	0.682	0.633	0.576	0.143	0.00	2.034
					Weighted total		1.661

[a] NHLA = National Hardwood Lumber Association, MOE = modulus of elasticity.

Table 17.—Relative worth using the relative strength to grade ratio by MOE range for soft maple.[a]

		MOE distribution ($\times 10^6$)					
		>2.0	1.8–2.0	1.5–1.8	1.2–1.5	<1.2	Total
	Value	Relative strength to grade ratio					
NHLA grade	US$/MBF	1	0.9	0.75	0.6	0	
2A	860	8	20	19	13	0	60
2B	400	24	37	45	13	3	122
3A	400	20	34	66	29	5	154
3B	400	49	53	107	44	10	263
Total		101	144	237	99	18	599
NHLA grade		Relative worth by grade					
2A	860	0.291	0.052	0.247	0.047	0.000	0.637
2B	400	0.820	0.221	0.292	0.123	0.000	1.456
3A	400	0.341	0.263	0.377	0.185	0.000	1.166
3B	400	0.314	0.128	0.292	0.160	0.000	0.894
					Weighted total		1.053

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; MOE = modulus of elasticity.

stiffness for CLT layups of 1.2 by 10^6 psi (8.3 KPa), all the No. 2 and better NELMA graded red oak boards exceeded the minimum threshold and the No. 3 NELMA red oak boards showed only one board below the threshold. Of the 299 Below Grade NELMA boards, 93 percent still surpassed the minimum threshold. Similarly, for the soft maple all the No. 3 and better NELMA graded boards exceeded the 1.2 by 10^6 psi (8.3 KPa) minimum threshold, while 93 percent of the Below Grade NELMA boards met or exceeded the minimum threshold. With a visual override in place, the authors believe most, if not all, of the boards not meeting or exceeding 1.2 by 10^6 psi (8.3 KPa) would have been sorted out of the sample. This strongly implies that any effort to manufacture hardwood CLT should incorporate an MSR grading system, with a visual override, which would serve to minimize the extra volume of boards necessary to achieve an equivalent volume of surface measure–ready CLT boards.

In the context of this study, the volume of MSR rated boards needed to generate 1,000 feet^2 (92.9 m^2) of surface measure CLT-ready boards is estimated at 1.25 MBF (2.95 m^3) for red oak and 1.24 MBF (2.93 m^3) for soft maple. The excess footage is due primarily to the 6 board feet (0.014 m^3) in the rough boards versus 5 feet^2 (0.46 m^2) of surface measure in the CLT-ready boards. That is, there would be nearly a 1:1 ratio of unprocessed to CLT-ready boards if the unprocessed boards were roughly 6.5 inches (16.5 cm) wide.

Since there are no current markets and no companion pricing for structurally graded hardwoods, the relative worth calculations were an attempt to assess the worth of the various grades of NHLA lumber with respect to their probable NELMA yields. The results of the relative worth analysis for visually graded red oak and soft maple unexpectedly suggested that, for red oak, NHLA No. 3B Common have the highest relative net worth, while NHLA No. 2A and No. 2B soft maple have the highest relative worth. Using the weighted totals to compare species, soft maple performed the best (0.670), followed by yellow-poplar (0.595; see Table 20) and red oak (0.457). It is important to note that NHLA No. 2B, No. 3A, and No. 3B grades are generally sold green into pallet markets and not kiln dried. This creates a problem in estimating the kiln-dried pricing for use in the relative worth analysis and requires an "educated guess" from the cooperating mill in this study.

The relative worth of yellow-poplar, based on the MOE distributions of boards in the Azambuja (2021) study is contained in Table 21. A comparison of the MOE-based weighted total relative worth between red oak, soft maple,

Table 18.—Volume of NHLA graded 4/4, rough, kiln-dried red oak and soft maple boards needed to yield 1,000 feet of surface measure of CLT-ready structural boards of No.2 and better, using visual grading.[a]

Red oak		Soft maple	
NHLA grade	MBF required for 1,000 feet^2 of surface measure in CLT-ready boards	NHLA grade	MBF required for 1,000 feet^2 of surface measure in CLT-ready boards
2A	3.16	2A	2.06
3A	3.60	2B	2.06
3B	3.56	3A	2.64
		3B	3.55

[a] NHLA = National Hardwood Lumber Association; CLT = cross-laminated timber, MBF = 1,000 board feet.

Table 19.—The volume of 4/4, rough, kiln-dried yellow-poplar required to yield 1 MBF of CLT-ready boards, by NHLA grade.[a,b]

NHLA grade	Board feet required to yield 1 MBF of CLT-ready boards
2A	2.73
2B	2.63
3A	3.34
3B	6.52

[a] NHLA = National Hardwood Lumber Association; CLT = cross-laminated timber; MBF = 1,000 board feet.
[b] From Azambuja et al. (2021).

Table 20.—Relative worth of 4/4, rough, kiln-dried yellow-poplar NHLA grade lumber according to price, frequency, and percent of clear strength, by NELMA visual grade.[a]

Structural grade		SS	No. 1	No. 2	No. 3	BG	Total
	Value	Relative strength to ratio					
NHLA grade	US$/MBF	0.66	0.6	0.49	0.3	0	
2A	500	75	31	88	90	157	441
2B	400	15	18	44	35	57	169
3A	400	41	24	62	58	169	354
3B	400	7	7	28	28	158	228
Total		138	80	222	211	541	1192
NHLA grade	US$/MBF	Relative worth by grade					
2A	500	0.224	0.084	0.196	0.122	0.0	0.627
2B	400	0.146	0.160	0.319	0.155	0.0	0.780
3A	400	0.191	0.102	0.215	0.123	0.0	0.630
3B	400	0.051	0.046	0.150	0.920	0.0	0.339
					Weighted total		0.595

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; SS = Select Structural; BG = Below Grade; MBF = 1,000 board feet.

Table 21.—Relative worth using the relative strength to grade ratio of MOE for yellow-poplar (Azambuja et al. 2021).[a]

		MOE distribution ($\times 10^6$)					
		>2.0	1.8–2.0	1.5–1.8	1.2–1.5	<1.2	Total
	Value	Relative strength to grade ratio					
NHLA grade	US$/MBF	1	0.9	0.75	0.6	0	
2A	860	67	86	198	162	11	424
2B	400	22	34	74	30	1	161
3A	400	19	66	152	94	12	343
3B	400	6	15	104	67	15	207
Total		114	201	528	253	39	1135
NHLA grade		Relative worth by MOE value					
2A	860	0.326	0.365	0.700	0.175	0.0	1.557
2B	400	0.342	0.475	0.862	0.280	0.0	1.958
3A	400	0.138	0.433	0.832	0.411	0.0	1.813
3B	400	0.072	0.163	0.942	0.486	0.0	1.663
					Weighted total		1.711

[a] NHLA = National Hardwood Lumber Association; NELMA = Northeastern Lumber Manufacturers Association; MOE = modulus of elasticity.

and yellow-poplar shows that yellow-poplar (1.711) is marginally better than red oak (1.661), while both are significantly better than soft maple (1.053).

The varying results between the relative worth of red oak, soft maple, and yellow-poplar reveal the issues associated with visual grading as a reliable measure for selecting boards for CLT production and further suggests that MSR grading of CLT boards is economically more efficient than visual grading, particularly in the 4/4, rough, kiln-dried volume necessary to achieve 1,000 feet^2 (92.9 m^2) of CLT-ready lumber (see Tables 18 and 19).

The total relative worth results, by NHLA grade, show that NHLA Grade No. 2B is the best choice for CLT lumber for both yellow-poplar and soft maple, from both visual and mechanical grading perspectives. For red oak, NHLA No. 3B was shown to be the best option for CLT production. Although not completely comparable, the MSR-based total relative net worth results were significantly higher than the visual grading results, resulting from the improved performance of Below Grade boards under a mechanical testing scenario.

Conclusions

Based on the results of this study, it would appear that visual grading underestimates the stiffness of hardwood boards of the two species tested in this study and in an earlier study on yellow-poplar. The most viable option, from both a technical and economic perspective, for CLT board production is to incorporate an MSR option, with a visual override, as recommended in the NELMA MSR rules. This option mirrors the results provided by Green et al. (1994) in their earlier studies of visual versus MSR type grading that found much better results with MSR grading of hardwood lumber.

Overcoming the fundamental difference between hardwood and softwood lumber in a structural application setting is the challenge that must be overcome for hardwood CLTs to become a viable opportunity for the hardwood industry. Attempting to incorporate structural lumber production into a traditional appearance-graded production facility can be a significant challenge that will take much thought and capital investment. It will, at a minimum, require a decision-making process that can efficiently move back and forth between the two types of lumber in a production setting. Ultimately, it may be necessary to create a hardwood mill that is focused solely on the production of structural lumber, with log breakdown, grading, surfacing, and drying components configured similar to a softwood mill producing dimension lumber.

CLT does represent a value-added opportunity for hardwoods, but hardwoods can only become a viable alternative if the various challenges can be overcome.

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