Using Low-Grade Hardwoods for CLT Production: A Yield Analysis

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ABSTRACT

Low-grade hardwood logs are the by-product of logging operations and, more frequently today, urban tree removals. The market prices for these logs is low, as is the value recovered from their logs when producing traditional forest products such as pallet parts, railroad ties, landscaping mulch, or chips for pulp. However, the emergence of cross-laminated timber (CLT) for building construction in North America may provide an additional and possibly a more valuable product market for low-grade, low-value hardwood logs. Using the RaySaw sawing and ROMI rough mill simulators and a digital databank of laser-scanned low-grade yellow-poplar (Liriodendron tulipifera) logs, we examine the yield-recovery potential for lumber used in the production of CLT.

1. INTRODUCTION

Cross-Laminated Timber (CLT) developed in the 1980s in Switzerland and Austria, are essentially large-scale, solid wood panels with windows and supply line openings pre-cut using CNC equipment in the manufacturing plant. The resulting panels leave the manufacturing plant on trucks ready to be installed at the construction site, where they are installed with cranes with minimal disturbance to the surroundings at a fast pace (Crespell and Gagnon 2011). Indications exist that CLT may be a cost-competitive construction method compared with concrete or steel, especially when all costs of erecting a building are accounted for (reThink Wood 2014, WoodWorks 2012).

Recently, CLT has been used for some tall buildings like the Stadthaus in London (Hopkins 2012, Lattke 2007), the Forte in Melbourne (Lend Lease Corporation 2013, Wells 2011), the Wood Innovation Design Center in BC, Canada (Partnership BC 2013), the Treet block of flats in Bergen, Norway (Economist 2016, The Nordic Page 2017) or the Brooks Commons Phase 1 building in Vancouver (Forestry Innovation Investment 2017). In the U.S., only a handful of small projects have been executed utilizing CLT. Examples include the Candlewood Hotel (The Redstone Rocket 2015), Franklin Elementary School (MSES Architects 2014) or projects under construction like the T3-Hines (Star Tribune 2015) or the Albina Yard (Albina Yard 2017). Currently, there are only 3 manufacturers of CLT in the country (Smartlam 2017, D.R. Johnson 2017, and Euclid 2017), where only one is APA/ANSI PRG 320 certified (D.R. Johnson 2017). The market potential for CLT in the US is estimated at 2.1 - 6.4 million m^3 annually, e.g., two to six times today's annual production worldwide (Karacabeyli and Douglas 2013, Espinoza et al. 2015, Laguarda-Mallo and Espinoza 2014).

Although at present, virtually all CLT structures are manufactured using softwoods, there is growing interest in the possibility of manufacturing CLT panels made from hardwoods. Hasslacher, a forest products company in Austria, built a single-family home in St. Magdalena, Austria with CLT made from Birch (Hasslacher 2015). Today, Hasslacher's material is commercially available with certification according to EN 1995-1-1 (European Standards 2004). The American Hardwood Export Council (AHEC) has promoted CLT made from yellow poplar (Liriodendron tulipifera), because it is abundant, inexpensive, has good mechanical properties compared to softwoods and is strong (AHEC 2017a). AHEC, together with cooperating companies, has built two demonstration objects to advance the use of hardwood CLT, i.e., "Endless Stairs (AHEC 2017b)" and "The Smile (AHEC 2017c, CNN 2016)". Thus, while research about hardwood CLT is scarce, results confirm that it is suitable for use and that the production of hardwood CLT is technically feasible (Hovanec 2015, Mahadzadeh and Hindman 2015, Jeitler et al. 2016, Franke 2016, Kramer et al. 2014).

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While hardwood CLT is not well established yet, it has the potential to become a major application for low value hardwoods from U.S. forests with important implications throughout the U.S. hardwood value chain. However, at the present time, little understanding exists as to the implications of a potentially increased use of hardwoods for the manufacturing of CLT. This lack of knowledge makes informed decisions difficult and uncertain. This study sought to create knowledge needed for making informed public policy and business decisions to allow the U.S. forest products industry and U.S. forest landowners, both public and private, to achieve maximum benefit from the emergence of this promising new construction material.

2. METHODS

A sample of 20 low-grade yellow-poplar (*Liriodendron tulipifera*) logs was randomly selected from two sites in the Central Appalachian region of the United States. The logs were graded to US Forest Service log grades to establish quality and market value (Rast et al. 1973). Under the Forest Service log grading rules, the best saw log grade is Factory 1, followed by Factory 2, and the lowest grade is Factory 3. As the grade decreases, the number of severe defects increase, and the length of clear areas, and number of clear faces decrease. Although the rules include Construction and Local Use as the lowest quality grades, these are not commonly sawn to produce graded lumber. However, the price and yield characteristics of the logs could make them suitable for the production of CLT timbers. For the purposes of this paper, any log grading lower than Factory 3 is described as below grade. Table 1 lists the logs and their quality, dimensions, and market value. Market value was determined by using an average of prices mills are paying for logs at the time of publication.

Table 1: Dimensions, grades, and market values of the sample logs.

Log #	**FS Log Grade**	**Length**	**Scaling Diameter**	**Taper**	**Sweep**	**Log Market Value**	**Debarked Log Volume**
		(meter)	(cm)	(mm per m)	(cm)	**(USD)**	**(m3)**
1	Below Grade	3.5	38.1	10.3	4.1	3.56	0.61
2	Factory 3	3.3	38.1	1.1	1.2	8.90	0.49
3	Below Grade	3.4	35.6	1.8	4.3	2.88	0.43
4	Factory 3	4.6	43.2	8.4	1.7	16.20	0.96
5	Factory 3	4.3	27.9	2.1	1.3	5.00	0.34
6	Factory 3	4.1	33.0	0.0	4.3	7.30	0.41
7	Factory 2	3.9	30.5	9.9	2.9	11.80	0.38
8	Factory 2	3.4	30.5	1.5	3.5	9.80	0.29
9	Below Grade	4.7	43.2	3.2	9.0	6.48	0.93
10	Factory 3	2.9	48.3	3.5	3.1	12.10	0.64
11	Factory 3	3.0	30.5	12.4	6.7	3.90	0.34
12	Factory 3	5.0	33.0	10.1	4.6	9.70	0.66
13	Factory 2	5.2	43.2	4.8	3.0	37.00	1.03
14	Factory 3	4.0	40.6	15.7	7.1	11.90	0.71
15	Factory 2	3.5	38.1	10.8	3.7	17.80	0.55
16	Factory 2	3.4	30.5	6.0	8.4	9.80	0.35
17	Factory 3	4.5	27.9	5.2	5.4	5.50	0.37
18	Below Grade	2.7	40.6	5.6	2.0	16.60	0.41
19	Below Grade	2.8	35.6	0.0	3.2	5.80	0.35
20	Below Grade	3.1	35.6	12.0	2.3	7.20	0.42
Total						**209.22**	**10.68**

The log sample was imaged using the US Forest Service high-resolution laser scanner (Thomas et al. 2006 and 2008) and all surface defects were measured and recorded. This process results in a complete digital representation of a log that allows determination of accurate shape and volume measurements (Thomas and Bennett 2014). Figure 1 shows a scan of log number 14 (Table 1) from this study rendered in 3D. Note the large knots visible on the log shown in Figure 1. Overall, there were a total of 172 knots found on the 20 logs in the sample, with the average knot size being 152mm long and 157 mm wide. In addition, the largest knot found measured 597 mm by 368 mm.

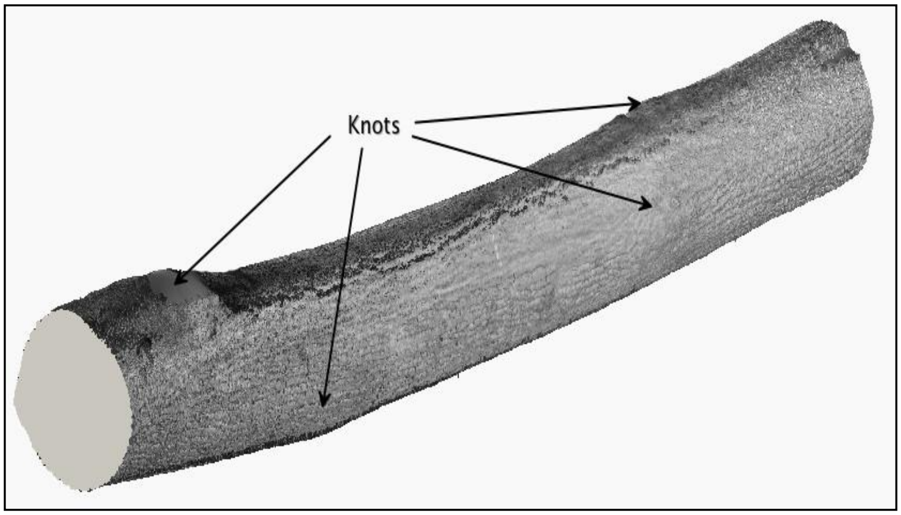

Figure 1. High-resolution laser-scan of yellow-poplar log 14.

2.1. *SAWING SIMULATION*

The RaySaw sawing simulator (Thomas 2013) was used to process the 20 laser-scanned yellow-poplar logs listed in Table 1 digitally into virtual timbers. RaySaw was configured to simulate a band sawmill operating with a 5mm thick kerf. Defect types, sizes, and locations on the timbers were predicted using modeled relationships among external defect indicators and internal features (Thomas 2009, 2016). The target thickness of the dried and surfaced CLT lamination layers was set to 34 mm, following the European Standard FprEN 16351 (European Committee for Standardization 2015). To determine the target green thickness to saw with RaySaw we added a green allowance based on yellow-poplar tangential shrinkage factor of 8.2% (i.e., 4 mm, Forest Products Laboratory 1999) a surfacing allowance of 6 mm, and a sawing variation of 1 mm. Using the tangential shrinkage factor provides a maximum drying loss and provides a conservative estimate of recovery. Thus, RaySaw was configured to saw rough timber of 45 mm thickness. Figure 2 shows an end view of log #5 (Table 1), including defect locations with a typical sawing pattern used in this study. Note, that in the sawing pattern used, we maximized the width of the timber that results from the clear face of the log. We then simulated drying by shrinking the timbers using the tangential shrinkage factor of 8.2% (Forest Products Laboratory 1999).

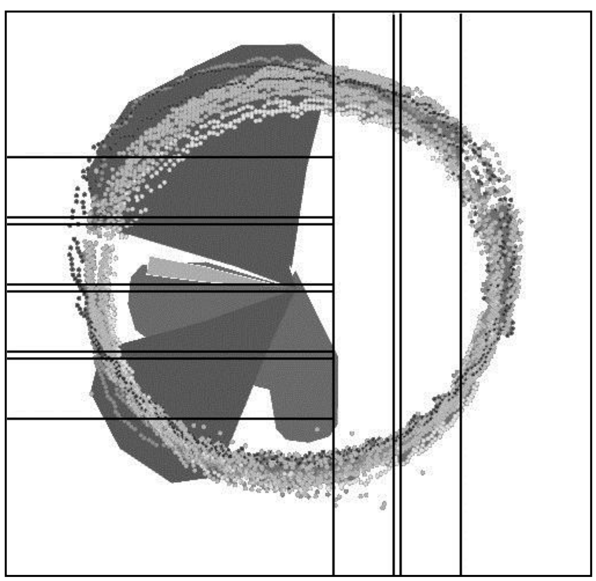

Figure 2. RaySaw sawing pattern design window for log # 5.

The digital timbers from RaySaw (Thomas 2013) are roughly edged (i.e., contain some wane) and contain defects not allowed for the manufacture of CLT. To remove these defects and generate material meeting manufacturing specifications (European Committee for Standardization 2015), we used the ROMI simulator (Thomas et al. 2015). ROMI processes rough random width and length timber lumber and produces dimensional parts that meet the user's size and grade specifications. An important component of the ROMI simulation is that it reports the number and volume of parts produced as well as the number of cutting operations required to achieve those results. Although ROMI can process parts using a rip-first, chop-first, or combined rip and chop-first combined operation, we used only its rip-first processing capabilities. This processing mode is the most common in real-world mills and traditionally offers greater mill throughput than do other processing modes.

2.2. CLT PRODUCTION SPECIFICATIONS

In our simulations, CLT production was configured to meet the requirements outlined in the European Standard FprEN 16351 (Timber structures - Cross laminated timber - Requirements - Final Draft, European Committee for Standardization 2015) and in the American Standard ANSI/APA PRg 320-2012 (ANSI/APA 2012). We simulated the production of three-layered panels and used edge-bonded timber layers rather than plain timber layers. For plain timber layers, the minimum lamination timber width for a 34mm lamination is 136mm (European Committee for Standardization 2015). However, for some of the logs in our sample, it would not be economical to obtain material this wide. Though, for edge-bonded timber layers, the European standard does not specify a minimum lamination timber width, yet the American standard (ANSI/APA 2012) specifies a minimum timber width of 1.5 times the lamination thickness, or 51mm for a 34 mm thick layer. Thus, we used 51 mm as the minimum acceptable timber width. We simulated the production of finger-jointed timbers with 20 mm long fingers. The minimum and maximum length of the timbers finger jointed was 200 mm and 5 meters, respectively.

The European standards ignore knots less than 6 mm in diameter, and exclude knots larger than 6 mm from a zone 20 mm plus 3 times the knot diameter from the end of the timber. However, the defect proximity rules were implemented in ROMI control defect placement only along the lengthwise edges of the strip, not along the ends (Thomas et al. 2015). Thus, to overcome this shortcoming of the ROMI software, two different simulation analyses were performed: one produced clear, defect free lamination timbers, the second produced sound lamination timbers and allowed defects as large 50 cm^2 on 90 mm and wider timbers, and defects up to 15 cm^2 on 51 mm wide timbers. Thus, the clear timber analysis provides a conservative baseline yield, while the sound simulations that allowed defects points to the full yield potential of using lower grade yellow-poplar for CLT production. In addition, our simulated drying process does not degrade the timbers, i.e., it does not "introduce" splits, checks, and warp normally encountered in the drying process. Thus, the results shown may be somewhat higher than can be expected in reality.

3. RESULTS

Typically, when hardwoods are sawn, they are sawn such that the opening cut results in a timber of at least 100 mm wide for Common grade timber, or 150 mm for Selects and Better grades. However, in this study, we were sawing to maximize the production of timber for CLT manufacture. Thus, more flexibility in the design of the sawing patterns than sawyers normally has existed. By narrowing the opening face, we were able to reduce the amount of wood in the slabs (i.e., residues) and increase recovery on some logs. Table 2 lists the volumes and the number of timbers obtained from each log as well as production yields for the clear and the sound simulation analysis using RaySaw (Thomas 2013). Overall, 177 rough dimensioned timbers totaling 4.5 m^3 (dry volume) were sawn from 10.7 m^3 of logs.

3.1. PRODUCTION YIELDS

Table 2 presents the yield in CLT timber for the clear and the sound simulations for each log used in the simulations. For the clear simulations, primary yields ranged from a low of 58.44% to a high of 88.28% with an overall average yield of 71.24%. For the sound analysis, the results are similar. Here, yield for individual logs ranged from a low of 58.96% to a high of 89.15%, with an overall average yield of 71.84%. One might expect a greater difference in yield between the clear and sound analyses. However, we ran the simulation and put higher prioritization values on wider and longer part sizes. Thus, a wider or longer part is preferred over any combination of shorter, or narrower parts that could be cut from an area, even when a greater yield could be obtained. This was done to ensure the production of larger lamination timbers, which would require less handling and be more economical to glue-up into CLT panels.

While the clear and sound CLT production yields may seem similar, there are major differences. For the clear simulation runs, there were a total of 780 lamination timbers produced, while 7% fewer timbers, i.e., 722, were produced by the sound timber simulations. Given that .03 m^3 more volume was produced in the sound timber simulations, results indicate that longer parts were produced, reducing the need for costly finger jointing.

Table 3 lists the total length of laminations timber obtained from each log by length. Wider lamination timbers require fewer glue-joints and involve less handling and labor during production than narrower timbers. For the clear simulations, 488.58 lineal meters of timbers 110 mm and wider widths were produced. However, the sound simulations produced 540.44 lineal meters in the 110mm and wider widths, or 5% more. Further, examining the results by timber width shows that the clear simulations produced narrower lamination timbers (51 to 90 mm wide) compared to the sound simulations. Thus, a shift to wider parts occurred with the sound simulations thanks to the inclusion of certain timber characteristics. This is due to the ROMI simulator prioritizing wider and longer parts more than narrower and shorter parts, but is also a testament that the inclusion of a limited set of timber characteristics does not only improve yield, but also leads to longer and wider pieces being cut from the available resource. Interestingly, this preference can result in slightly lower overall yield in some cases as seen with timbers produced from log 1, where the clear simulation resulted in 74.55% yield, versus 74.19% for the sound simulations (Table 2). However, the sound simulation produced 3 meters more lamination timbers of 130mm wide from log 1 than did the clear simulation (Table 3).

Table 2. Yield and production overview for the clear and the sound timber production simulations.

			Clear Timber Simulation Results			Sound Timber Simulation Results		
Log Number	Dry Timber Volume	Board Count	Part Count	Primary Yield	Primary Part Volume	Part Count	Primary Yield	Primary Part Volume
	(m3)			(percent)	(m^3)		(percent)	(m^3)
1	0.281	13	54	74.55	0.209	49	74.19	0.208
2	0.239	12	40	59.23	0.141	42	61.98	0.148
3	0.158	10	41	64.59	0.102	41	65.20	0.103
4	0.363	10	57	79.25	0.288	49	80.39	0.292
5	0.127	6	18	76.15	0.097	17	78.64	0.100
6	0.160	7	46	61.72	0.098	40	68.07	0.109
7	0.149	7	11	81.91	0.122	10	82.64	0.123
8	0.127	7	32	74.80	0.095	29	76.86	0.098
9	0.382	10	70	68.83	0.263	68	69.00	0.264
10	0.349	13	39	73.94	0.258	38	74.07	0.259
11	0.108	7	19	88.28	0.095	17	89.15	0.096
12	0.328	9	64	58.44	0.192	60	58.96	0.193
13	0.500	12	54	74.91	0.375	49	73.39	0.367
14	0.253	9	37	66.89	0.169	38	68.91	0.174
15	0.210	8	31	79.23	0.176	26	78.63	0.165
16	0.121	4	24	70.02	0.085	22	70.91	0.086
17	0.158	6	33	64.39	0.102	22	66.09	0.105
18	0.173	10	29	71.12	0.123	45	69.40	0.135
19	0.123	8	32	69.18	0.085	32	71.15	0.088
20	0.195	9	49	68.25	0.133	28	71.33	0.123
Total	4.504	177	780	71.24	3.209	722	71.84	3.236

Table 3. Lamination timber width production overview.

Log Number	Clear Timber Simulated Production					Sound Timber Simulated Production				
	51mm	90mm	110mm	130mm	150mm	51mm	90mm	110mm	130mm	150mm
	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
1	19.39	14.02	6.64	13.44	8.56	16.22	11.17	6.64	16.43	8.57
2	13.18	12.66	16.89	0.00	2.65	13.18	7.81	22.63	0.00	2.65
3	5.87	5.13	16.75	0.00	2.29	5.87	5.13	17.00	0.00	2.29
4	19.71	8.99	41.67	0.00	12.55	19.72	8.99	42.63	0.00	12.63
5	3.87	6.61	3.86	7.18	4.15	3.87	6.84	3.86	7.71	4.15
6	12.93	0.83	10.61	3.41	3.29	7.67	6.06	8.53	6.05	3.08
7	1.13	3.65	6.46	10.69	6.81	1.13	3.82	6.46	10.76	6.86
8	6.01	5.53	6.11	2.71	6.04	6.01	6.08	6.14	2.83	6.08
9	28.49	10.29	21.89	4.87	14.24	25.63	11.22	22.62	4.87	14.24
10	25.18	14.18	18.98	2.72	16.10	25.37	14.18	19.01	2.72	16.10
11	6.92	5.64	5.22	6.72	2.85	6.92	5.64	5.28	6.72	2.98
12	21.95	10.96	13.39	5.08	7.91	21.97	11.03	13.55	5.72	8.04
13	39.71	22.17	28.62	3.71	20.77	43.04	17.78	23.78	7.38	21.18
14	19.47	5.34	19.90	2.58	5.79	22.44	5.07	20.07	2.58	5.80
15	20.31	3.19	9.95	3.43	12.75	16.71	3.20	6.53	3.43	16.20
16	10.26	3.91	6.07	0.00	5.94	10.26	3.91	6.09	0.00	6.14
17	9.51	7.53	3.35	5.79	4.28	6.80	4.24	3.83	6.16	7.03
18	14.16	10.50	11.98	2.55	1.43	14.08	4.79	9.43	2.62	9.06
19	3.71	3.30	3.00	3.56	1.37	9.10	6.86	3.50	5.41	2.36
20	15.17	6.44	7.57	4.29	7.19	14.16	10.50	11.98	2.62	1.43
Total	296.94	160.89	258.89	82.72	146.97	290.15	154.31	259.55	94.02	156.87

4. DISCUSSION

Although early yield experiments using the RaySaw (Thomas 2013) and the ROMI (Thomas et al. 2015) simulation software showed that CLT lamination timbers of 170 mm and wider can obtained from the resource, doubts exist that lamination timbers this wide would be suitable for CLT production. It is common for lumber from low-grade (yellow-poplar) logs to exhibit cupping and bowing during the drying process and resulting in high degrees of crook or sweep, as seen in logs 9,11,14, and 16 (Table 1). Thus, production of 170 mm and wider laminations timbers will likely result in low production yield after drying. Thus, we limited our study to 150mm and narrower timbers. However, further research is needed to investigate the implications of width on yield of lamination timbers after drying and the relationship of lamination timber width and the glue-up of CLT panels in respect of process and of mechanical properties.

The average yield difference between the clear and sound defect was only 0.60%. One reason for this small yield difference is due to the characteristics of the resource. Lower grade logs, by their grade definition, will contain more and larger knots than higher grade logs. In the log sample used in this study, the average surface knot measured 152 mm long by 157 mm wide, which means that rather large knots existed internally. With a large number of the lamination timbers sawn containing knots larger than allowed in the specifications for sound lamination timbers, yield gain due to knot inclusion in the lamination timbers sawn was rather small. Further research is needed to better understand the relationship between the type and size of allowable characteristics in the lamination timbers, yield improvements, drying results, and mechanical properties of the resulting panels.

5. CONCLUSIONS

Rising interest in cross-laminated timber (CLT) by builders and the public have raised the question about CLT made of hardwoods. The technical feasibility of hardwood CLT has been shown and some model applications have been executed. Special attention is being paid to yellow poplar (*Liriodendron-tulipifera*) CLT panels, as yellow poplar is a strong yet rather light material, which is well suited for certain building applications. This study investigates the yield from low-grade yellow poplar logs for the manufacture of CLT panels.

This study focuses on low-grade yellow poplar logs as they are the by-product of logging operations and, more frequently today, urban tree removals. As the market value of such logs is limited, they may offer an economic source for the raw material needed for the manufacture of CLT panels. Possibly, increased demand for such logs, which historically have been used for traditional forest products such as pallet parts, railroad ties, landscaping mulch, or chips for pulp, may increase their market price and thus help landowners in their quest for profits.

Using the RaySaw sawing and the ROMI rough mill simulator and a digital databank of laser-scanned low-grade yellow-poplar logs, we examine the yield-recovery potential for lumber used in the production of CLT. The simulated sawing and cut-up of 20 low-grade yellow poplar logs resulted in overall primary part yields of 54% to 88% depending on the geometry and the characters found in particular logs for clear parts, i.e., no characters allowed in the resulting timbers. The overall average yield found for this simulation run was 71.24%. When allowing a limited set of characters in the lamination timbers, yield did not change much with the overall average yield found to be 71.84%. However, when a limited set of characters are accepted in the lamination timbers, wider widths and longer timbers are produced, helping to minimize the cost of fingerjointing and minimize the number of glue joints lengthwise. However, further research is needed to understand the relationship between the acceptance of characters and their size in lamination timbers to yield improvements and to the mechanical properties of resulting panels.

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