Techno-Economic Analysis for Manufacturing Cross-Laminated Timber

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Cross-laminated timber (CLT) is a bio-based building material that enables rapid construction and buildings with low embodied energy. Despite its comparative maturity in European markets, relatively little information regarding process design and economics for the manufacture of cross-laminated timber is available in the literature. Two techno-economic analyses were conducted to quantify the mill-gate cost of cross-laminated timber. The cross-laminated timber manufacturing process was described, and costs were analyzed for two facility scales. Cross-laminated timber produced at the large-scale facility using lumber priced at an average value for the northwest United States has a minimum selling price of $536/m^3. Sensitivity analyses were used to define the impact of plant size, asset utilization, lumber price, plant capital cost, material waste, and other variables on minimum selling price. The cost of cross laminated timber rises quickly when a facility is not fully utilized. The second-ranking cost controlling variable is lumber price, while energy prices have minimal influence. The price of cross laminated timber can be optimized by locating a facility near low-cost lumber. The lowest-price region analyzed was the southeast United States using Southern Pine, which reduced the cost of cross laminated timber to $518/m^3.

Keywords: Format; Cross-laminated timber; CLT; Techno-economic analysis; TEA, Mass timber; Ratio factor

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INTRODUCTION

Interest in cross-laminated timber (CLT) for mid- and high-rise buildings is growing in North America. As the United States population concentrates in urban areas, architects are increasingly aware of CLT as an environmentally sustainable building material. However, as the industry seeks to expand to fill the potential demand, little public information is available regarding the process economics of the process.

Cross-laminated timber is categorized as a mass timber building product composed of orthogonal layers of lumber, called lamella or plies that are bound together, most often using a thermosetting resin. The alignment of the primary axis for the lumber alternates 90 degrees between adjacent plies. However, if specific properties are needed for an application, adjacent plies can be oriented in the same direction (Karacabeyli and Douglas 2013).

Although it is just now gaining momentum in North America, CLT is not a new building material. Its development began in the 1990s in Europe, which is still the manufacturing hub with 80% of the global production (Karacabeyli and Douglas 2013; Grasser 2015; Espinoza *et al.* 2016; Oregon Best 2017). The European market is relatively mature compared to its North American counterpart, but it is still projected to continue growing at 10% a year (Pahkasalo *et al.* 2014). The global volume in 2015 was estimated at 1 million m^3 (Muszyński *et al.* 2017). Grasser (2015) found that, in general, each existing CLT manufacturing facility reported an increased production volume from 2013 to 2014. This increase could have resulted from a variety of factors including, improved uptime, adding shifts, better press utilization via improved loading and unloading, improved resin chemistry, or greater focus on manufacturing thick panels used in large buildings.

Interest in CLT has grown in the United States with plants manufacturing structural CLT currently operated by DR Johnson (https://oregonclt.com/), SmartLam (http://www.smartlam.com/), and International Beams (http://internationalbeams.com). Sterling manufactures CLT for use as mats, but they are not included, as this product is engineered for a different function (https://www.sterlingsolutions.com). Additional facilities have been announced and are expected to start production soon. Sturcturlam (https://www.structurlam.com/) and Nordic Structures (https://www.nordic.ca/) are the only two operating Canadian manufacturers with a combined yearly volume of 110,000 m^3 (Espinoza *et al.* 2016).

The current voluntary product standard, ANSI/APA PRG 320-2018, requires the parallel direction lamina to be comprised of at least visual grade No. 2 lumber. Although visual grade No. 3 can be used in the transverse direction, the wane and warp characteristics may present manufacturing challenges. Smith and Larson (2017) state that CLT may be a good outlet for lower quality lumber, including beetle kill, forest thinnings, and fire recovery harvests. The use of low-grade lumber has been listed as a benefit of CLT, especially in the cross-ply directions and at or near the center of the panel (Crespell and Gagnon 2010, Stauder 2013). However, depending on the application of the CLT, significant lumber culling may be required.

A shortage of techno-economic analyses for CLT was found in the literature. Bédard *et al.* (2010) completed a comprehensive analysis of capital and operating expenses and an in-depth review of the process, but the proprietary report is not widely available. Grasser (2015) investigated the CLT market, compiled a European and North American industry status review, and designed multiple CLT manufacturing lines with capital costs. This report however did not include operating costs, compute minimum selling prices, or return on investment. Beck (2015) completed a high-level economic feasibility study, but the details do not allow researchers to change variables to determine their impact. Anderson (2016) presented more detail than the Beck study at the 2016 Mass Timber Conference, this talk can be viewed only on video, and the report is proprietary.

The goal of this research was to conduct a robust techno-economic analysis for CLT production. Specifically, the objectives were to produce a process design for two plausible plant sizes, compute minimum selling prices under a variety of operating conditions to underpin a sensitivity analysis and provide a realistic view of total investment costs for such facilities.

EXPERIMENTAL

CLT Facility

A techno-economic analysis was completed for two hypothetical CLT manufacturing facilities, a small and large-scale facility (52,000 and 87,000 m^3/yr). Muszyński *et al.* (2017) completed a survey of existing CLT facilities worldwide and found plant sizes that range from 500 to 100,000 m^3 per year in 2015. The large facility size was chosen to be like a new facility that might be erected, based on the facility scale observed in Europe (Karacabeyli and Douglas 2013; Grasser 2015; Espinoza *et al.* 2016; Muszyński *et al.* 2017). The average size of a CLT facility in Europe is larger than in North America. The mean and median European production for 2013 and 2014 were nominally 25,500 m^3 and 8,500 m^3, respectively (Grasser 2015). The smallest production was only 700 m^3, while the largest capacity reported was 105,000 m^3. In the current study, the large-scale plant is capable of manufacturing just over 87,000 m^3/yr if the facility runs 24 hours a day, 7 days a week with 90% uptime.

The smaller scale plant in our study has a capacity of 52,000 m^3/yr with the same operating assumptions as the larger facility. However, literature assumptions of a single operating shift are common (Bédard *et al.* 2010; Crespell and Gagnon 2011; Muszyński *et al.* 2017). Asset utilization was evaluated as a variable and was included in the results section showing the impact of yearly production volume on CLT minimum selling price (MSP). It is plausible that a plant would start with one shift and add shifts as the demand grows, and the present analysis will show the financial result of this operating decision.

The manufacturing process design was the same for both mill sizes (Fig. 1). It was assumed that kiln-dried lumber was received and stored until it entered the process. The lumber was visually graded before a moisture content check. Though the lumber purchased was kiln dried, the process design considered a re-dry step to meet the 12 ± 3% target specified in PRG 320-2018. All pieces that were out-of-specification for moisture content were sent to the dry kiln. Lumber defects were trimmed before finger-jointing. The finger-jointed lumber was cut to length and then assembled into parallel and transverse layers. Resin was applied to the face of each layer before panel assembly. No edge bonding of the lumber was assumed, which was consistent with many European plants. Brandner (2013) suggested that new press technology can achieve a zero-gap layer without the need for edge bonding. The panel layup was sent into the press, followed by sanding, trimming and required computer numerical control (CNC) routing to prepare the panel for pre-transport packaging. The resin selected for the process model was a polyurethane (PUR), which matches the operating methods outlined in Bédard *et al.* (2010). Muszyński *et al.* (2017) reported 65% of the responding CLT manufacturers use PUR. The second most popular resin is melamine urea-formaldehyde (Muszyński *et al.* 2017). In the large-scale plant, the press size was 2.4 m by 18.3 m, with the width chosen to facilitate transportation of finished panels. For the small-scale facility, the press size was 2.4 m by 11.0 m. Numerous factors influenced the CLT production volume of a given plant that operated at full capacity. These factors included both the mix of panel thicknesses and press cycle time, assuming a press-constrained mill design. Here, a press cycle time of 45 minutes was assumed, which includes both loading and unloading. This time conservatively fit within the press time range of 15 to 60 minutes presented in the literature (Mohammad *et al.* 2012; Karacabeyli and Douglas 2013). The impact of press cycle time was further explored in the sensitivity analysis. The panel thickness mix was assumed to be 89% 5 ply, 5% 7 ply, and 6% 9 ply. The impact of this choice was addressed in the sensitivity analysis.

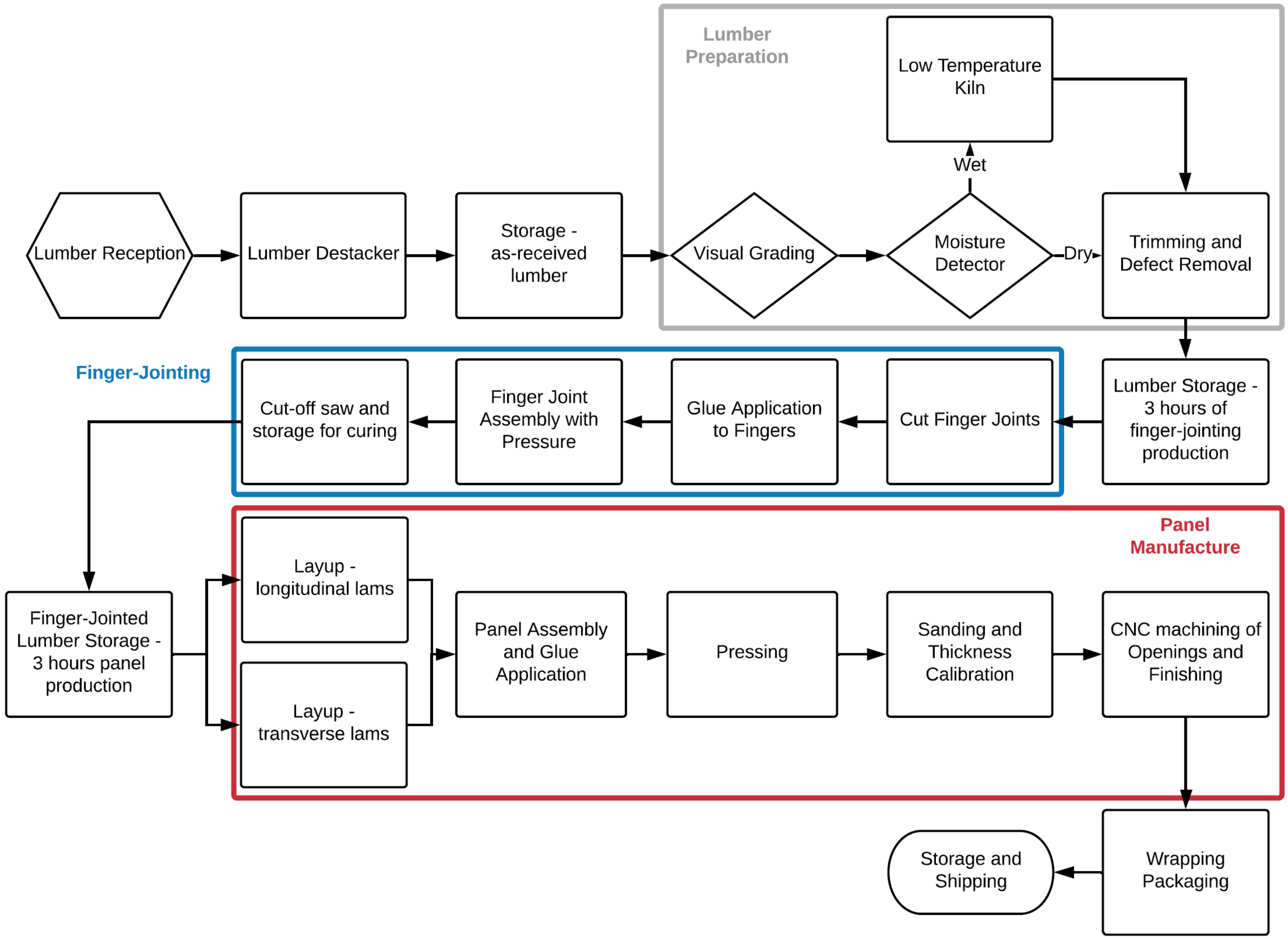

Fig. 1. CLT process flow diagram

Economic Analysis

A techno-economic analysis was completed for both facility scales. Capital and operational costs varied between these scenarios, but the underlying financial assumptions were held constant (Table 1). The cost year used throughout this paper is 2015, the plants were funded assuming 30% equity, a loan interest rate of 8%, and a ten-year term. The average United States inflation rate of 2% from 1997 to 2016 (CPI 2018) was applied throughout. The average corporate income tax paid from 2008 to 2012 in the United States of 16.9% was used in the analysis (Bann *et al.* 2017). The plant life was assumed to be 20 years after construction is completed. The facility could likely operate longer but would require a significant, unknown, capital infusion. Working capital was often listed as a percentage of capital costs (Humbird *et al.* 2011; de Jong *et al.* 2015). However, working capital was used to cover expenses to run a facility when the cash flow did not meet the needs (Peters *et al.* 2003). For that reason, working capital was assumed to be 20% of the yearly operating costs (Brandt *et al.* 2018).

Table 1. Economic Analysis Parameters for Small and Large Scale CLT Facilities

Economic Parameter	Value
Cost Year	2015
Plant financing	30% equity
Plant Life	20 years + 3 years for construction
Income tax rate	16.9%
Inflation	2%
Land	1.5% TCI[a]
Working Capital	20% OPEX
Depreciation schedule	7 years, MACRS schedule [b]
maintenance	6% TPEC[a]
Ratio Factor (FCI)	4.4[a,c]

[a] Peters *et al.* 2003, [b] Modified Accelerated Cost Recovery System (IRS 2017), [c] FCI ratio factor for a greenfield solid processing plant

A nominal financial analysis was utilized following the method outlined by Petter and Tyner (2014) and Brandt *et al.* (2018). The MSP was determined by selecting a nominal financial discount rate and setting the net present value to zero. A nominal financial discount rate was determined using a real discount rate combined with inflation. For this analysis, the real discount rate was set at 10%, which combined with 2% inflation results in a nominal financial discount rate of 12.2%.

Capital Costs

The capital cost to build a CLT facility can be discussed in different terms. The total delivered equipment cost (TDEC) was one way to study the cost of a facility. However, the total capital investment (TCI) was the amount of capital required to fund the entire facility and included equipment, installation, buildings, site preparation, and working capital. It was chosen here to apply ratio factors to the inside battery limit (ISBL) TDEC to determine the fixed capital investment (FCI). Outside battery limit equipment and indirect capital costs were estimated using ratio factors (Peters *et al.* 2003). Ratio factors were used extensively for estimating capital costs in the literature (Zhang 2013; de Jong *et al.* 2015; Martinkus and Wolcott 2017; Brandt *et al.* 2018). This method of estimating capital costs had an accuracy of ± 20 to 30% (Peters *et al.* 2003). Ratio factors were applied to ISBL TDEC to estimate the costs outside of the battery limits as well as the installation of equipment and indirect costs (Peters *et al.* 2003). The delivered equipment costs were a combination of quotations and literature sources. USNR generously provided the cost information for the lay-up equipment, resin application process, and the pneumatic CLT press. One way to reduce TCI is to locate a facility adjacent to an existing plant or choose a closed site to repurpose. Both options reduced the applicable ratio factor, thus decreasing the TCI.

The CLT facility was divided into five ISBL departments: (1) lumber preparation, (2) finger jointing, (3) panel lay-up and resin application, (4) pressing, and (5) panel finishing. Each department was evaluated for scalability. Not all departments can be scaled between the two facility sizes. The lumber preparation department can be scaled and includes visual grading for both the small and large-scale facilities as well as a dry kiln to ensure the lumber moisture content meets ANSI/APA PRG 320-2018 at 12% ± 3%. The finger-jointing department cost was not reduced based on plant scale because a single line was included. Reduction in productivity in this department would likely be controlled by reducing the line speed, reducing the shifts or both. The panel finishing department was similar for the two plant sizes, over half of the cost of this department was represented in the CNC machine, which does not scale down. It should be noted that a product mix that requires intense use of the CNC equipment for the large-scale facility may require a second machine, and this cost was not included in this analysis. The press was scaled linearly, reduced by a press unit length facilitated by the modular design of the USNR press. This design allowed the smaller scale facility to add press modules in the future as demand increases, assuming the other departments can also be scaled to meet the increased throughput. The costs for each department, total purchased equipment cost (TPEC), and TCI are listed in Table 2 for both the large and small-scale facilities.

Bédard *et al.* (2010) reported a total purchased equipment cost of $22.7 million Canadian dollars, which is higher than was determined for this project. Two major differences are that Bédard *et al.* (2010) included machine stress rated (MSR) grading and edge gluing of each layer.

Table 2. Capital Costs for Small and Large Scale CLT Facilities

Department	Small Scale (MM$)	Large Scale (MM$)
Lumber Preparation	2.1	3.0
Finger Jointing	2.7	2.7
Lay-up/Resin Application	1.4	1.9
Press	1.5	2.4
Panel Finishing	5.8	6.6
TPEC	13.5	16.6
TCI	64.6	80.2

Operating Costs

Operational costs were obtained from the literature or estimated from the USNR quotes and are listed by department in Table 3 (Peters *et al.* 2003; Bédard 2010; Reeb 2011; Jones *et al.* 2013). The cost of labor was modified by combining the Jones *et al.* (2013) salary information, and Bédard *et al.* (2010) headcount requirements by shift. The single largest operating cost category was lumber purchase, which is 41% of the large-scale facility operating costs. Lumber cost was determined using regional commodity data provided by Random Lengths with an added transport cost (Torrey and Murray 2016; Random Lengths 2018). It was assumed that the lumber would be transported an average of 100 miles and the round-trip cost added to the lumber prices. The price utilized was specific to the northwestern US region averaged over 2011 to 2015 for kiln-dried No. 2, 2 x 6 lumber. The same grade and size were used for parallel and transverse plies. The parallel direction requires at least a No. 2 visual grade, and the transverse direction requires a nominal 6 in width for the 2 by thickness (ANSI/APA PRG 320-2018). It should be noted that lumber prices are volatile and can greatly impact the financial viability of CLT panels. For this reason, the lumber cost was included in the sensitivity analysis.

Table 3. Yearly Operating Costs for Small and Large CLT Facilities

Department	Small Scale (MM$)	Large Scale (MM$)
Lumber Preparation	0.3	0.4
Finger Jointing	1.2	2.0
Lay-up/Resin Application	3.3	5.6
Press	0.2	0.3
Panel Finishing	0.1	0.1
Lumber Purchase	9.1	15.2
Fixed Operating Costs	12.0	13.2
Total	26.2	36.9

RESULTS AND DISCUSSION

The techno-economic analyses for the small and large-scale facilities were completed to determine base case results. The analysis spreadsheets for the base-case small and large-scale CLT facilities are available from the authors as supplementary materials. Variables were manipulated to determine the importance of operating, financial, and location choices. The material that was lost in grading and processing is assumed to be of similar value to hog fuel and is sold.

Base Case Comparisons

Results are discussed using base case scenarios for both the small and large facilities. These scenarios are defined, including CLT price, in Table 4. The electricity and natural gas costs are average, national industrial values for 2011 to 2015 (EIA 2018a, EIA 2018b). The Northwest lumber type was a simple average of the cost of the values reported in Random Lengths for 2011 to 2015 for Douglas Fir, inland Fir and Larch, Spokane White Fir and Hem-Fir, and coastal Hem-Fir and Spruce-Pine-Fir (SPF) (Random Lengths 2018). Beck used a historical, delivered lumber cost of $140/m^3 ($330/mbf) for a study focused on Northern California and added $11/m^3 ($25/mbf) for additional drying (2015). Bédard *et al.* (2010) used a value of $191/m^3 ($450/mbf) for redried MSR spruce, which is a higher cost grade than assumed for this study.

It is clear from the mill-gate CLT price that the large-scale facility is more economically viable. This is a result of economies of scale and asset utilization. Both facility scales require a finger-jointing line and CNC router. These pieces of equipment are expensive and are not easily scaled down, meaning that they are not fully utilized at the small-scale facility. The cost of CLT is below the $600/m^3 mill-gate value quoted by Bédard *et al.* (2010). Beck (2010) listed an average market price of $742/m^3. The small-scale facility is within the literature range at $652/m^3. The base case for the large-scale facility was used for the sensitivity analysis. A subset of the variables reviewed is in Fig.

2. The percent of each panel thickness was chosen to match the structural designs in Dolan *et al.* 2019.

Table 4. Base Case Scenario Variable Values for Both Large and Small-Scale Facilities

Variable	Large-Scale	Small-Scale
Lumber Type	Northwest	Northwest
Delivered Lumber Cost	$152/m³ ($359/mbf)	$152/m³ ($359/mbf)
Lumber Delivery Cost	$3.2/m³ ($7.8/mbf)	$3.2/m³ ($7.8/mbf)
Ply Count Ratio (5: 7: 9)	89%:5%:6%	89%:5%:6%
Loss through Process	15%	15%
Operating Hours per Year	7862	7862
Electricity Cost	$0.069/kWh	$0.069/kWh
Natural Gas Cost	$4.51/MMBtu	$4.51/MMBtu
Mill-gate CLT MSP	$536/m³	$652/m³

Production Volume

Asset utilization, reported in terms of hours per day and days per week, was the single most influential variable. In a developing market, such as CLT in North America, it was very important to consider this factor because incoming orders may not be sufficient to maintain full-time operations. This impact was not included in the primary sensitivity analysis (Fig. 2) to keep the scale meaningful for the other variables. The impact of full asset utilization, meaning operating a facility 24 h a day, 7 days a week is not unexpected. By reducing the operation to only 12 h per day, the cost of CLT increases by $180/m^3, or 33%. This influence on selling price should caution manufacturers to build a facility that is sized to run below full capacity and then increase production volume when demand increases (Fig. 2). Although not as efficient as a large-scale facility, a small-scale facility running 24/7 will produce CLT with an MSP of $652/m^3.

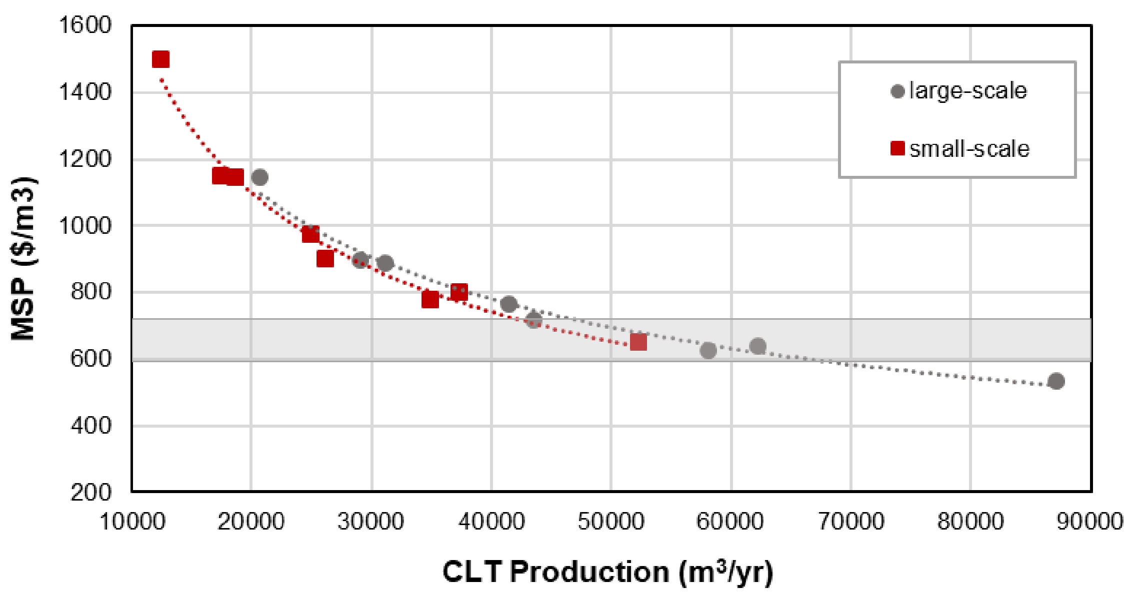

Fig. 2. Impact of yearly production volume on minimum selling price (MSP) for small and large-scale facilities. The grey area shows literature values of CLT prices ($600-742/m³)

The curves shown in Fig. 2 illustrate the need to run a mill with as high of asset utilization as possible. Muszyński *et al.* (2017) surveyed existing facilities in 2015, and many were planning to expand production by adding shifts and increasing efficiency. The addition of shifts is unrealized capacity that already exists, and Muszyński *et al.* (2017) reported an average of 1.1 shifts worked at CLT facilities in 2015.

The impact of press cycle time influences MSP like asset utilization, as both impact production volume. Decreasing press time increases volume through a facility. If the press cycle time is decreased to 30 minutes while maintaining the other base case assumptions, the cost of CLT drops by $77/m^3 or 14%. Bédard *et al.* (2010) assumed a 25-minute press cycle time; however, if the press cycle time is increased to 60 or 75 minutes, the cost increases the MSP by $80 or 15% and $160/m^3 or 30%, respectively. Even with a press cycle time of 75 minutes, the MSP of CLT would land within the grey region in Fig. 2, which defines the range of literature costs.

Sensitivity Analysis

Lumber price, capital investment, assumed discount rate and resin price have the largest influence on CLT price (Fig. 3). As with all commodities, lumber prices can be volatile. Although the -30% cost value shown in Fig. 3 did not result in an average price in the 2011-2015 timeframe, the Northwest average lumber price dropped below that value in both 2008 and 2009. The average price for 2017 was above the + 30% value by $6.8/m^3 ($16/mbf), which increased the cost of CLT by an additional $62/m^3 or 12%. Even when using five-year averages within the Northwest, the price of lumber varies and was generally lower in the western part of the region than in the eastern side. Random Lengths 2018 published data for No.2 2 x 6 lumber for a variety of locations within the United States. The price used to represent the southeastern US is the average of all Southern Pine prices, while the price for the eastern US SPF is the average of the delivered SPF lumber prices to Chicago, Boston, Ohio/Western Pennsylvania, and Atlanta.

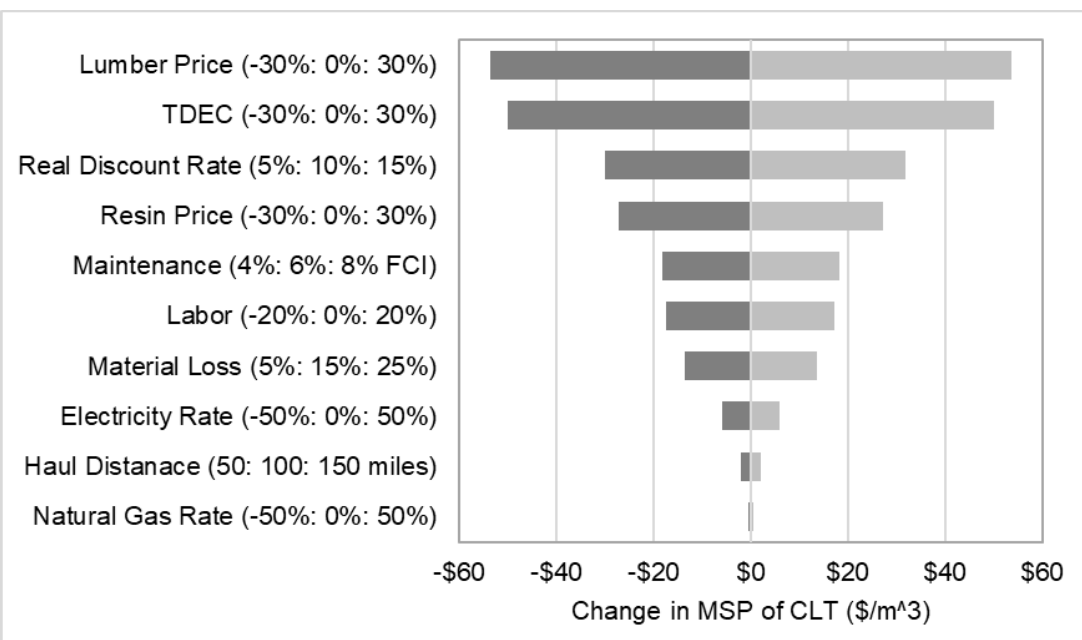

Fig. 3. Changes in minimum selling price (MSP) of CLT based on changes to baseline variables, listed on y-axis in parenthesis, of manufacturing variables from base case cost of $536/m^3. Total delivered equipment cost is abbreviated TDEC.

These regional lumber prices are worth considering when locating a CLT facility. For instance, Southern Pine had a lower price than Northwest lumber, and when used in CLT the MSP decreases from \$536/m^3 to \$518/m^3. In contrast, the eastern SPF price of lumber is higher than the other regions. A facility choosing to locate in this region would have an increased CLT price of \$559/m^3. The prices used in this analysis are regional averages. Specific locations within each region will yield higher or lower costs. Each location should be studied before selecting a facility location.

Different lumber grades can be chosen based on the structural requirements of the panel. The prices discussed in this paper assume all No. 2 grade lumber. However, the use of lower grades in the cross plies is an option if the structural panel requirements can be met. Some customers may prefer higher grade lumber that may allow for a thinner panel or better visual aesthetic. The non-standard nature of the CLT panel business makes complete price analyses difficult.

A drop in TDEC will also decrease CLT cost, whether through the purchase of used equipment, contract negotiation with a manufacturer, the removal of the CNC machine, or co-location with an existing facility. However, the removal of the CNC machine will limit the facility from making panels that require more in-depth finishing. Muszyński *et al.* (2017) reported that of the survey responders, 96% produce custom panels, which require CNC finishing. However, it was noted that one facility made only solid panels with no machining, and these panels should be expected to bring a lower price. Others have suggested that a manufacturer could mitigate risks by entering the market with floor panels that typically do not require computer-controlled machining and are simpler to implement from a code perspective (Crespell and Gagnon 2010). The other side of the CAPEX influence is increased capital expenditures. If the capital costs to build a facility exceed the budget, or a more complicated process increases the initial capital spent, the MSP will also increase.

It is possible that lumber could be purchased for a premium with moisture tolerances that meet the manufacturing specifications. This approach could eliminate the capital and operating costs of a dry kiln. Beck (2015) suggested a \$11/m^3 (\$25/mbf) premium to reduce the MC to the CLT requirements. If the lumber is No. 2, it will need to be inspected for wane, but a strategic supplier could cull No. 2 boards with low wane for use in CLT production, theoretically dropping the need for visual grading and thus the costs. It must be noted, however, that such an approach would remove the control of two key operating risks from the CLT manufacturer, moisture control, and lumber quality. Such a strategy would require close coordination between the lumber suppliers and CLT producer and may require moving the quality assurance step to the lumber production facilities staffed by CLT employees. Such a scenario is beyond the scope of this analysis.

The total assumed material loss throughout the defect removal and the finger-joint process is 15% (Bédard *et al.* 2010). However, if a facility was able to procure lumber that would result in lower losses, for instance through the purchase of cut to length finger-jointed lumber, a CLT facility would be able to spend more on lumber, reduce the cost of CLT, or both. If cut to length finger-jointed lumber was purchased at the desired moisture content, the reduction in capital and operating costs combined with the same MSP would allow a facility to pay \$74/m^3 (\$174/mbf) more than simple commodity lumber. If the loss is held constant at 15% and lumber is simply purchased at the desired moisture content, eliminating the capital and operating costs for a dry kiln, lumber can be purchased for \$19/m^3 (\$45/mbf) more, which is nearly double the \$11/m^3 (\$25/mbf) suggested by Beck (2015). However, Beck (2015) did state that this value should be verified.

The real discount rate was chosen based on the common use of 10% internal rate of return (IRR) in a discounted cash flow rate of return (DCFROR) analysis. However, it is reasonable that investors may require a greater return, especially with the volatility of building material prices (Bédard *et al.* 2010; Crespell and Gagnon 2010; Beck 2015). Even though changing the real discount rate to 15% increases the MSP to \$568/m^3, a 6% escalation, the MSP still falls within the range listed in the literature. The same is true for the impact of resin price on MSP. Although, CLT price is influenced by resin price, even with 30% change in resin price, the CLT MSP changes only 5% or \$27.2/m^3.

Product mix can influence the average panel price. For instance, the MSP can be reduced by manufacturing thicker panels by increasing overall press throughput with minimal changes in press cycle time. The base case assumes a product mix of 89% 5 ply, 5% 7 ply, and 6% 9 ply panels. If the product mix is changed to make all 5 ply panels, the cost of CLT increases 3% to \$552/m^3. Producing thicker panels allows a greater throughput, which reduces the burden of capital on a volume basis. However, this choice is limited by the supporting equipment, for example, dry kiln, finger jointer, lay-up, or panel finishing capacities. Wall panel demand is expected to grow at a slower rate than the demand for floor panels (Beyereuther *et al.* 2016). If lateral loads, especially in taller buildings, require thicker panels as was the case in Dolan *et al.* (2019), the demand for thicker panels may be delayed.

Impact of MSP on Total Building Cost

Most of the remaining variables studied in the sensitivity analysis did not have a significant impact on the MSP. However, the impact of even small price changes when considered based on the total building cost may influence purchasing decisions. To demonstrate this, two buildings sizes were chosen to compare costs: 2323 and 6968 m^2 (25,000 and 75,000 ft^2). The volume of CLT per floor area of the building is referenced here as a CLT use factor. Bédard *et al.* (2010) presented two CLT use factors: 0.20 and 0.26 m^3/m^2 (0.64 and 0.86 ft^3/ft^2).

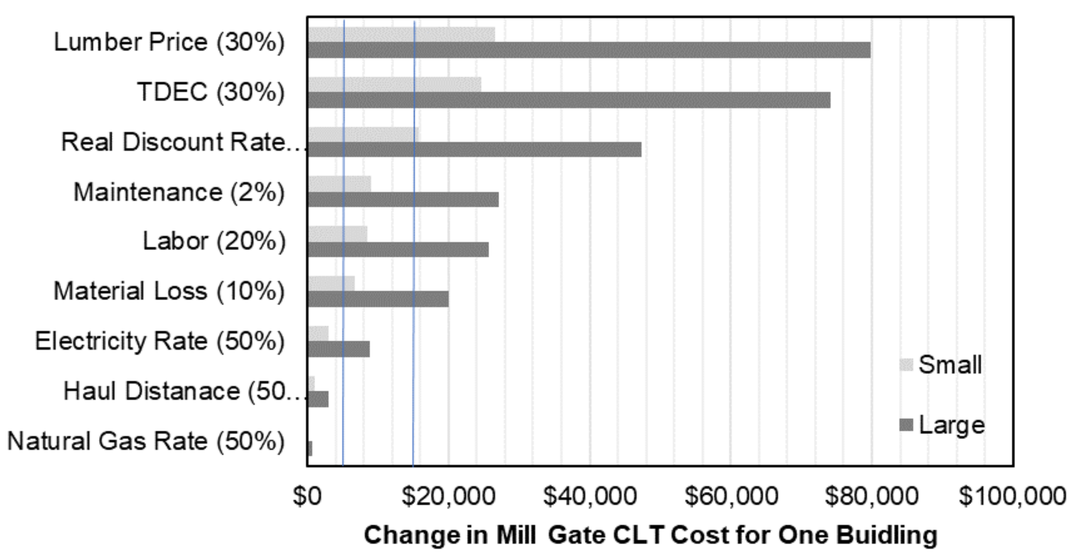

Fig. 4. Cost change for a single building based on variable changes at mill gate for large and small-scale facilities. The blue lines are at \$5000 and \$15000, the assumed values that will influence CLT purchase.

Bédard *et al.* (2010) conservatively assumed the lower CLT use factor for the estimated North American demand values. Crespell and Gagnon (2010) listed values from European buildings that ranged from 0.15 m^3/m^2 (0.49 ft^3/ft^2) to 0.46 m^3/m^2 (1.5 ft^3/ft^2), with most above 0.30 m^3/m^2 (1.0 ft^3/ft^2). The authors believe that a reasonable assumption for demonstrating the cost change for a single building is a CLT use factor of 0.21 m^3/m^2 (0.7 ft^3/ft^2). This CLT use factor combined with the small and large building scenarios yields 500 and 1500 m^3, respectively, rounded to the nearest 100 m^3.

Each building project budget will be able to handle cost changes differently. The authors assume that for 2323 and 6968 m^2 buildings, the threshold for differences that will influence the purchase of CLT are $5000 and $15000, respectively. These minimum cost change values combined with the sensitivity data presented in Fig. 4 demonstrate that the impact of lumber price, TDEC, and discount rate are not the only variables that may influence a project choosing CLT. A facility should also consider maintenance costs (± 2% FCI), labor costs (± 20%), and material loss (± 10%).

CONCLUSIONS

1. The base case cost of cross-laminated timber (CLT) is $536/$m^3$. The assumed real discount rate of 10% might not be sufficient for a new manufacturer to enter the market, and higher returns could be required. Holding all other variables constant and increasing the real discount rate to 20% the CLT price will increase to $601/$m^3$, which virtually matches the value $600/$m^3$ given by Bédard *et al.* (2010), which is observed in Europe.
2. Asset utilization, capital costs, discount rate, and lumber costs dominate the estimated MSP in this analysis. It is financially essential to run a facility at full production volume through 24/7 shifts and by running the shortest technically attainable press cycles. With increased production volumes, higher real discount rates can be attained with a reasonable MSP.
3. MSP is also influenced in a less significant way by other variables such as maintenance, labor, and material loss. These items could be a decision point when the cost difference for a single building project is observed.
4. MSP is dependent on TCI and can be dropped by co-locating with or repurposing an existing facility. Siting decisions will influence MSP through local lumber costs, haul distances, energy costs, and labor costs.
5. The lowest cost lumber, the single largest operating cost, is Southern Pine. Locating a facility is the southeast US is predicted to drop the MSP to $518/$m^3$. Even within this region, there are location specific changes, with an MSP price difference of $8/$m^3$.

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REFERENCES CITED

Anderson, R. (2016). "A cross laminated timber manufacturing plant: If you build it, will the lumber come?" in: *2016 Mass Timber Conference*, Portland, OR, USA.
ANSI/APA PRG 320-2018 (2018). "Standard for performance-rated cross-laminated timber," American National Standards Institute, New York, NY, USA.
Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., Hileman, J. I., and Barrett, S. (2017). "The costs of production of alternative jet fuel: A harmonized stochastic assessment," *Bioresource Technology* 227, 179-187. DOI: 10.1016/j.biortech.2016.12.032
Beck Group (2015). *California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM): Phase II Project Summary Report: Feasibility Assessment of Potential Business Opportunities*, National Forest Foundation, Portland, OR, USA.
Bédard, P., Fournier, F., Gagnon, S., Gingras, A., Lavoie, V., and Robichaud, F. (2010). *Manufacturing Cross-laminated Timber (CLT) Technological and Economic Analysis* (Report No. 201001259-3257AAM), FPInnovations, Québec, Canada.
Beyereuther, T., Ganguly, I., Hoffman, and M., Swenson, S. (2016). *CLT Demand Model for the Pacific Northwest*, Washington State University, Pullman, WA, USA.
Brandner, R. (2013). "Production and technology of cross laminated timber (CLT): A state-of-the-art report," in: *Focus Solid Timber Solutions - European Conference on Cross Laminated Timber (CLT)*, Graz, Austria.
Brandt, K., Gao, J., Wang, J., Wooley, R., and Wolcott, M. (2018). "Techno-economic analysis of forest residue conversion to sugar using three-stage milling as pretreatment," *Frontiers in Energy Research* 6(77), 1-11. DOI: 10.3389/fenrg.2018.00077
CPI (2018). *CPI-All Urban Consumers*, United States Department of Labor, Washington, D.C., (https://www.bls.gov/cpi/data.htm).
Crespell, P., and Gagnon, S. (2010). *Cross Laminated Timber: A Primer*, FPInnovations, Vancouver, Canada.
Crespell, P., and Gagnon, S. (2011). *The Value Proposition for Cross-laminated Timber*, FPInnovations, Vancouver, Canada.
de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., and Junginger, M. (2015). "The feasibility of short-term production strategies for renewable jet fuels- A comprehensive techno-economic comparison," *Biofuels Bioproducts and Biorefining* 9(6), 788-800. DOI: 10.1002/bbb.1613
Dolan, J. D., Wilson, A., Brandt, K., Bender, D., Wolcott, M. (2019). "Structural design process for estimating cross-laminated timber use factors for buildings," *BioResources* 14(3), 7247-7265. DOI: 10.15376/biores.14.3.7247-7265
U.S. Energy Information Administration (EIA) (2018a). "Electricity: Detailed state data-Average price (Cents/kilowatthour) by state by provider, 1990-2016," (https://www.eia.gov/electricity/data/state/), Accessed March 9, 2018.
U.S. Energy Information Administration (EIA) (2018b). "Natural gas industrial prices," (http://www.eia.gov/dnav/ng/ngprisumaepg0pindmcfa.htm), Accessed February 28, 2018.
Espinoza, O., Buehlmann, U., Mallo, M. F. L., Trujillo, V. R. (2016). "Identification of research areas to advance the adoption of cross-laminated timber in North America," *BioProducts Business* 1(5), pp. 60-72.
Grasser, K. K. (2015). *Development of Cross Laminated Timber in the United States of*

America, Master's Thesis, University of Tennessee, Knoxville, TN, USA.
Humbird, D., Davis, R., Tao, L. Kinchin, C., Hsu, D., and Aden, A. (2011). *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover* (Report No: NREL/TP-5100-47764.), U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO.
IRS Publication 946 (2017). (https://www.irs.gov/publications/p946), Accessed April 3, 2018.
Jones, S., Meyer, P., Snowden-Swan, L., Padmaperuma, A., Tan, E., Dutta, A., Jacobson, J., Cafferty, K. (2013). *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-oil Pathway* (Report No: PNNL-23053, NREL/TP-5100-61178), U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO.
Karacabeyli, E., and Douglas, B. (2013). *CLT Handbook: U.S. Edition* (Report No: Special Publication SP-529E), FPInnovations, Pointe-Claire, QC, Canada.
Martinkus, N., and Wolcott, M. (2017). "A framework for quantitatively assessing the repurpose potential of existing industrial facilities as a biorefinery," *Biofuel Bioproducts and Biorefining* 11(7), 295-306. DOI: 10.1002/bbb.1742
Mohammad, M., Gagnon, S., Douglas, B. K., and Podesto, L. (2012). "Introduction to cross laminated timber," *Wood Design Focus* 22(2), 3-12.
Muszyński, L., Hansen, E., Fernando, S., Schwarzmann, G., and Rainer, J. (2017). "Insights into the global cross-laminated timber industry," *BioProducts Business* 2(8), 77-92. DOI: 10.22382/bpb-2017-008
Oregon Best. (2017). *Advanced Wood Product Manufacturing Study for Cross-Laminated Timber Acceleration in Oregon and SW Washington, 2017: A Catalytic Project of the Pacific Northwest Manufacturing Partnership*, Oregon BEST, Portland, OR, USA.
Pahkasalo, R., Aurenhammer, P., Bartolmé, O., and Gaston, C. (2014). *Value-Added Wood Products: UNECE/FAO Forest Products Annual Market Review, 2013-2014* (Report No: ECE/TIM/SP/36), UNECE/FAO Forestry and Timber Section, Geneva, Switzerland.
Peters, M. S., Timmerhaus, K. D., and West, R. E. (2003). "Analysis of cost estimation," in: *Plant Design and Economics for Chemical Engineers* (5^{th} Ed.), E. D. Glandt, M. T. Klein, and T. F. Edgar (eds.), McGraw-Hill Education, New Delhi, India, pp. 226-278.
Petter, R., and Tyner, W. E. (2014). "Technoeconomic and policy analysis for corn stover biofuels," *ISRN Economics* 2014, Article ID 515898. DOI: 10.1155/2014/515898
Random Lengths (2018). "My Print. Random Lengths Publications," (www.rlmyprint.com), Accessed January 11, 2018.
Reeb, J. (2011). "Compare costs of different fuels for drying lumber," in: *Portland International Center for Management of Engineering and Technology 2011 International Conference*, Portland, OR, USA.
Smith, D., and Larson, K. (2017). *Washington Mill Survey 2016* (Report No: 24), Washington State Department of Natural Resources, Olympia, WA, USA.
Stauder, C. (2013). *Cross-Laminated Timber: An Analysis of the Austrian Industry and Ideas for Fostering its Development in America*, Austrian Marshall Plan Foundation, Vienna.

Torrey, W. F., and Murray, D. (2016). *An Analysis of the Operational Costs of Trucking: 2016 Update*, American Transportation Research Institute, Arlington, VA, USA.

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