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Cost Analysis of Lightweight Wood Panels Strengthened with Lignin-Cellulose Nanofibrils

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Abstract

Oriented strand board (OSB) manufacturers would like to reduce panel weight to save on costs and provide a lighter panel for handling during construction. This study explored the possibility of making a lighter and cheaper oriented strand board (OSB) through the addition of lignin-retained cellulose nanofibers (LCNF). The main novelty of this study was that we created a standardized "cost ratio" table, which allows for a company to take their confidential adhesive and LCNF costs and easily determine if there is a projected increase or decrease in panel material costs (%) for lighter weight panels. To summarize the methodology, engineering and multivariate statistical methods were first used to develop predictive models of panel performance in the presence of a lower density and increased LCNF, for various adhesive amounts. Next, we used these models to calculate the amount of materials needed to achieve the same strength or stiffness. We then calculated the recipe costs for each scenario generated by the model. Our models revealed that a maximum density reduction of 0.05 g/cm^3 might be possible if the cost of LCNF (solid basis) is equivalent to pMDI (1:1 ratio); conversely, it was determined that LCNF was not cost effective if it was 7 times more expensive than pMDI (7:1 ratio).

Keywords: lignin, nanocellulose, low density, OSB, techno-economic

1. Introduction

Oriented strand board (OSB) manufacturers would like to reduce panel weight to save on costs and provide a lighter panel for handling during construction. Lighter panels would also help to reduce petroleum used during transportation within the supply chain. But reducing the density is not an easy task because most wood composite mechanical properties decrease with a decline in density (Schwarzkopf 2020). As such, OSB manufacturers have turned to engineering protocols as a way to reduce panel weight. Key past novel ideas toward OSB weight reduction include strategic placement of strands within the mat and manipulation of the vertical density profile (Xu and Suchsland 2007, Stürzenbecher et al. 2010). Today, improvements through engineering and efficiency have become very difficult, and new technologies are necessary to further weight reductions.

Cellulose nanocrystals (CNC) have been proposed as a way to either increase composite strength while lowering panel weight or increasing strength by 16% (Veigel et al. 2012). The area of nanotechnology has been classified as an emerging new sector in the forest business industry (Hansen et al. 2018). CNCs are derived from mechanical, chemical, or enzymatic treatment that yields rod-like structures of 2–10 nm in width and > 100 nm in length (Iglesias et al. 2020). The dry manufacturing cost of CNC has been reported to be $1.82 to $2.21/lb (de Assis et al. 2017). The overall all price may be higher/double after allowing for transportation and value upgrades to the final customer. One way to lower the cost is to leave residual lignin on the fiber during pulping. One study demonstrated a significant reduction in costs per dry pound, when residual lignin was left on the nanofiber (LCNF) (Delgado-Aguilar et al. 2016). Based on this review, it is anticipated that LCNF is less than the $2.21 as reported by de Assis et al. (2017). But

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realistically, these LCNF costs are just estimates and not derived from a real manufacturing process. Additionally, companies are not likely to report their real pMDI costs because of competition and antitrust concerns. In order to anticipate this uncertainty in costs, an analysis that standardizes the costs would be very useful.

Polymethylene poly(phenyl isocyanates) or polymeric MDI (pMDI) is an isocyanate polymer that is increasingly being used in OSB as an alternative to phenol formaldehyde (PF). Phenol formaldehyde is a concern due to the end-customer perception of hazardous formaldehyde emissions within the home. Often during manufacturing, a mixed production system is used where PF is applied to the surface layer while pMDI is applied to the core. However, over the last decade, more companies are using pMDI in both the surface and core, even though the pMDI will stick to the platen during pressing (Asafu-Adjaye et al. 2020). The advantages of pMDI for this study are that it reacts well with LCNF, resulting in strength improvement (Chen et al. 2019). A good bond between LCNF and pMDI is important, if we want to reduce costs by removing wood flakes.

This paper develops a "cost ratio" such that a manufacturer can reference our tables and determine if their input costs of LCNF and pMDI will yield cost savings on an equal strength basis (as determined through engineering methods). A target of equal strength is important because it means the product will meet the same strength requirement at a lower input materials cost.

2. Methods and Materials

The methods for materials selection, LCNF mixing/addition, OSB manufacture, and mechanical testing can be viewed in Hornus (2019). The softwood fiber was produced through a Kraft pulping process (Hornus 2019). For this study, we modeled the response of these properties to changes in panel density, adhesive loading, and LCNF addition (substitution into pMDI adhesive). The properties modeled from Hornus (2019) were dry modulus of elasticity (MOE) and modulus of rupture (MOR). It should be noted that internal bond (IB) and panel thickness swell with water exposure were also tested, but were not modeled in this study because MOE and MOR were the limiting factors for this data set (see Hornus 2019 for details around all properties tested). It should also be pointed out, for the sake of transparency, that IB exhibited some decrease with LCNF addition. So from a business perspective, a mill would not benefit from this cost reduction study if IB is their limiting factor; more work is needed beyond this study for IB improvement.

2.1 Statistical Modeling

For statistical model formulation, a factorial design was employed in which the mechanical, physical, and internal bond properties were the dependent variables, while LCNF, density, and adhesive loading were key factors. Specifically, the density was varied between 0.45, 0.55, and 0.65 g/cm^3; the pMDI adhesive loading was varied between 2.7%, 4.4%, and 6.2%; and the LCNF substitution into pMDI was varied between 0%, 3%, and 6%.

For this data set, there were no interaction effects between adhesive and nanofiber for any of the mechanical or physical properties (Hornus 2019). Therefore, only the main effects were used in building the models of the mechanical and physical properties: i.e., local density, LCNF, and pMDI adhesive loading.

2.2 Panel Cost Estimation

It was desirable to compute the costs of total raw materials as a function of density or weight per cubic dimension. The following calculations were performed to estimate total material costs.

Board weight (lb) = (lb / ft^3) / (width * length * thickness) [1]

Square footage per board (ft^2) = width*length [2]

Number of boards per MSF = 1000 ft^2 / square footage per board [3]

Cost of pMDI per board ($) = Board weight * (pMDI cost in $/lb) * %pMDI loading [4]

Cost of wood per board ($) = Board weight * (wood cost in $/lb) * % * wood weight [5]

Cost of LCNF per board ($) = Board weight * (LCNF cost in $/lb) * % LCNF dry weight [6]

Total cost per board ($) = Cost of pMDI per board + Cost of wood per board + Cost of dry LCNF per board [7]

Cost per MSF ($) = Total cost per board * Number of boards per MSF [8]

Then the difference in cost as computed by equation [8] for the control versus the lighter weight LCNF wood composite was calculated as a percent increase or decrease. Equation [7] could have also been used to achieve the same outcome.

It should be noted that Tables 2 and 3 allow for any cost range to be entered as long as the cost of LCNF is 1 to 10 times higher than pMDI. For our study, we assumed wax was $1/lb, but since this was not a factor in the design, it had no impact on the cost analysis. The cost of wood and pMDI for this study was $0.10/lb and $1.00/lb respectively. It is important to note here that that wood costs were 1/10th of pMDI costs. Companies who use Tables 2 and 3 should ensure this 1/10th relationship/assumption is still true for their cost scenarios. If this is considerably different, then the company may need to prorate or inflate the output of this table, a method which is beyond the scope of our paper.

3. Results and Discussion

The data are not shown, but our analysis found no interaction between the independent variables for any of the seven properties tested. This simplified the final models to be a simple multiple linear regression with no interaction terms (Table 1). Of the seven properties tested, all had positive slopes except IB, but only dry MOE and MOR were significant (LCNF p-value < 0.05). Thus, we only analyzed dry MOE and MOR for determining cost estimates for this study. Table 1 shows the effect of each variable on MOE and MOR. As can be seen, LCNF% and density were most important in determining MOE and MOR.

These models were next used to determine what combination of adhesive, LCNF, and density was needed to reach the same MOE or MOR. This strategy will allow us to determine if cost savings are possible through LCNF addition followed by a reduction in density. For example, in 2017 we had a confidential contact tell us that the LCNF cost would be greater than $1.00/lb, while an OSB company advised that the costs of pMDI and wood were $1.00/lb and $0.10/lb, respectively. Under these assumptions, the following graph was created to show how one can make a lighter and cheaper panel by substituting 6% LCNF into pMDI, while maintaining panel strength (Figure 1). A savings of approximately $23 per MSF was possible, while a lighter and equally strong board was available for the consumer.

It should be emphasized that Figure 1 is hypothetical, and that, realistically, we do not know the cost of LCNF or pMDI. LCNF is not yet commercial in many parts of the world, and we have to rely on experimental studies to estimate this value. Likewise, we have found that companies tend to give us inflated costs for pMDI, presumably so that they can keep their cost advantage confidential and avoid an antitrust lawsuit. In the future, one also does not know the impacts of inflation on material costs. As such, there is a need for a standardized method to this analysis, where companies can input their own costs into the model to see whether cost savings are possible. Tables 2 and 3 demonstrate this strategy, where a company can input their confidential cost ratio (LCNF:pMDI) and then see if the change in cost increases or decreases in the form of a percentage. The company can then translate the percentage into a real cost value for their financial situation.

The following examples summarize how to read Tables 2 and 3. If our specifications or end customer

Table 1. Full multiple linear regression model for dry MOE and MOR properties (n = 69 samples per model).

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation Factor
Property dry MOE						
Intercept	1	-27.615	531.51	-0.05	0.9587	0
Adhesive %	1	-22.211	37.14	-0.60	0.5519	1.06
LCNF %	1	48.75	21.91	2.22	0.0296	1.06
Density	1	5826.0	1030.28	5.65	<0.0001	1.11
Property dry MOR						
Intercept	1	-10.14	4.62	-2.20	0.0317	0
Adhesive %	1	0.010	0.32	0.03	0.9762	1.06
LCNF %	1	0.307	0.19	1.70	0.0499	1.06
Density	1	52.61	8.95	5.88	<0.0001	1.12

Table 2. MOE model predictions optimized such that each combination of independent variables will yield the same MOE.

Combination of LCNF, Adhesive %, and Density needed to reach same MOE (3410 MPa)	Density Reduction (g/cm^3)					
	0.0	0.01	0.02	0.03	0.04	0.05
Adhesive %	2.6	2.6	2.6	2.6	2.6	2.6
LCNF %	0	1.2	2.4	3.6	4.8	6.0
Δ Cost (%)$_{10:1}$	0	**-0.3**	**-0.5**	**-0.7**	**-1.0**	**-1.2**
Δ Cost (%)$_{5:1}$	0	**-1.1**	**-2.1**	**-3.2**	**-4.3**	**-5.3**
Δ Cost (%)$_{1:1}$	0	**-1.7**	**-3.5**	**-5.2**	**-6.9**	**-8.7**
Adhesive %	4.4	4.4	4.4	4.4	4.4	—
LCNF %	0.8	2	3.2	4.4	5.6	—
Δ Cost (%)$_{10:1}$	0	**-0.2**	**-0.4**	**-0.6**	**-0.9**	**—**
Δ Cost (%)$_{5:1}$	0	**-0.9**	**-1.9**	**-2.8**	**-3.8**	**—**
Δ Cost (%)$_{1:1}$	0	**-1.5**	**-3.1**	**-4.6**	**-6.2**	**—**
Adhesive %	6.1	6.1	6.1	6.1	—	—
LCNF %	1.6	2.8	4	5.2	—	—
Δ Cost (%)$_{10:1}$	0	**-0.2**	**-0.4**	**-0.6**	**—**	**—**
Δ Cost (%)$_{5:1}$	0	**-0.9**	**-1.7**	**-2.5**	**—**	**—**
Δ Cost (%)$_{1:1}$	0	**-1.4**	**-2.8**	**-4.2**	**—**	**—**

Note: a "—" means that an LCNF > 6% was needed to reach the same MOE and is not considered possible due to a viscosity limitation (difficulty spraying). The analysis also assumes water in LCNF is negligible in cost (de Assis et al. 2017). **Bolded** sections in the table represent model output of the change in costs (%).

Table 3. MOR model predictions optimized such that each combination of independent variables will yield the same MOR.

Combination of LCNF, Adhesive %, and Density needed to reach same MOR (21.5 MPa)	Density Reduction (g/cm^3)					
	0.0	0.01	0.02	0.03	0.04	0.05
Adhesive %	2.6	2.6	2.6	2.6	2.6	2.6
LCNF %	0	1.9	3.6	5.3	—	—
Δ Cost (%)$_{10:1}$	0	**0.8**	**1.2**	**1.7**	**—**	**—**
Δ Cost (%)$_{5:1}$	0	**-0.6**	**-1.3**	**-2.0**	**—**	**—**
Δ Cost (%)$_{1:1}$	0	**-1.6**	**-3.3**	**-5.0**	**—**	**—**
Adhesive %	4.4	4.4	4.4	4.4	4.4	4.4
LCNF %	0.1	1.8	3.5	5.2	—	—
Δ Cost (%)$_{10:1}$	0	**0.4**	**0.8**	**1.3**	**—**	**—**
Δ Cost (%)$_{5:1}$	0	**-0.6**	**-1.3**	**-1.9**	**—**	**—**
Δ Cost (%)$_{1:1}$	0	**-1.5**	**-3.0**	**-4.4**	**—**	**—**
Adhesive %	6.1	6.1	6.1	6.1	6.1	6.1
LCNF %	0.1	1.7	3.4	5.1	—	—
Δ Cost (%)$_{10:1}$	0	**0.3**	**0.6**	**1.0**	**—**	**—**
Δ Cost (%)$_{5:1}$	0	**-0.6**	**-1.2**	**-1.7**	**—**	**—**
Δ Cost (%)$_{1:1}$	0	**-1.4**	**-2.7**	**-4.0**	**—**	**—**

Note: a "—" means that an LCNF > 6% was needed to reach the same MOR and is not considered possible due to a viscosity limitation (difficulty spraying). Analysis also assumes water in LCNF is negligible in cost (de Assis et al. 2017). **Bolded** sections in the table represent model output of the change in costs (%).

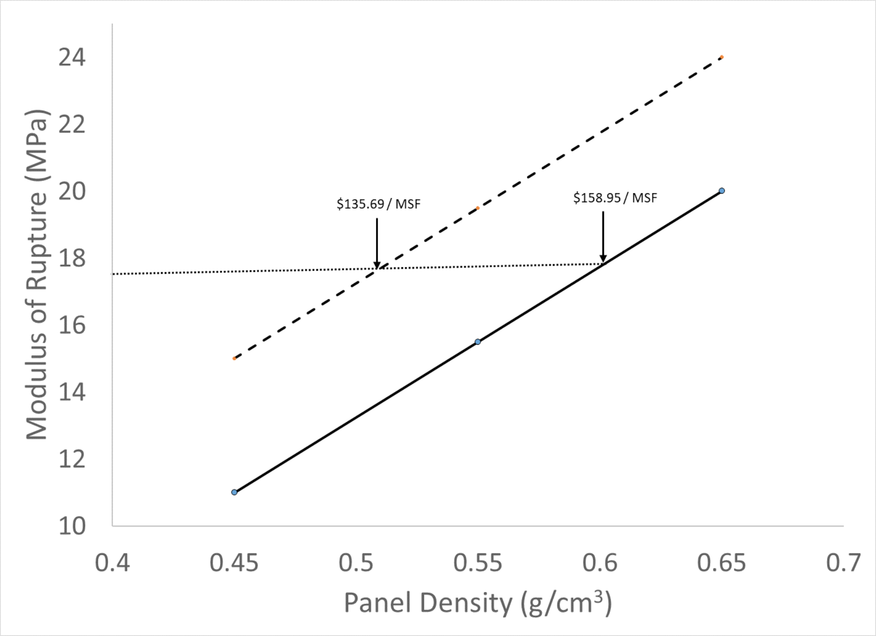

Figure 1. A combination of the multivariate model (from Table 1) and the cost model from equations [1]–[8], in which the bottom solid line represents the predicted strength of a control at 4% pMDI loading, and the dashed top line represents the same conditions but with the substitution of 6% LCNF into the pMDI.

places a priority around strength (MOR), then we would focus on Table 3. If we assume a 6% adhesive loading, a 1.7% addition of LCNF, a density reduction of 0.01 g/cm^3, and a cost ratio of 5:1 (LCNF:pMDI), then the model says that the percent costs will decrease by 0.6%. Conversely, if our specifications or end customer dictates that material stiffness (MOE) is important, then we would focus on Table 2. Under this scenario, if we assume a 2.6% adhesive loading, a 6% addition of LCNF, a density reduction of 0.01 g/cm^3, and a cost ratio of 5:1 (LCNF:pMDI), then the model says that the percent costs will decrease by 1.2%.

Using interpolation of Tables 2 and 3, or using the models described in Table 1 and equations 1-8, we determined the breakeven point to be at or close to 7:1 for most scenarios. In other words, if we want to reduce costs while making lightweight panels with LCNF, then the cost of LCNF needs to be no more than 7 times that of pMDI.

According to Table 2, the addition of LCNF appeared to show more promise for cost reduction for dry MOE than dry MOR. In other words, the addition of LCNF to maintain MOE was cheaper for all adhesive, loading, and density combinations. This would suggest that MOR is the limiting factor for this study, if the company has to maintain their product above a specific strength specification.

For dry MOE, we showed the potential to simultaneously reduce the density and cost by 0.05 g/cm^3 and 8.7%, respectively (Table 2). This means that we can make a lighter weight panel that can meet the needs of construction, while being easier to handle. Likewise, we can create a lighter panel that reduces gasoline costs during transportation. It also allows us to use less wood to make the same square footage of panels.

4. Conclusions and Recommendations

Oriented strand board (OSB) manufacturers would like to reduce panel weight to save on costs and provide a lighter panel for handling during construction. In summary, it was concluded that a lighter OSB could be achieved with the addition of LCNF. We were able to maintain mechanical properties (strength and stiffness) while lowering panel density. A break-even cost ratio analysis found that the LCNF% could be up to 7 times more expensive than pMDI, while still yielding a cheaper OSB panel. While not discussed extensively in this paper, for future work, it is recommended that manufacturers and researchers continue to work on how to improve dispersion methods, as this will likely increase density reductions and further reduce costs with LCNF additions.

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