Techno-Economic Analysis of Lignin-Containing Micro- and Nano-Fibrillated Cellulose for Lightweight Linerboard Packaging

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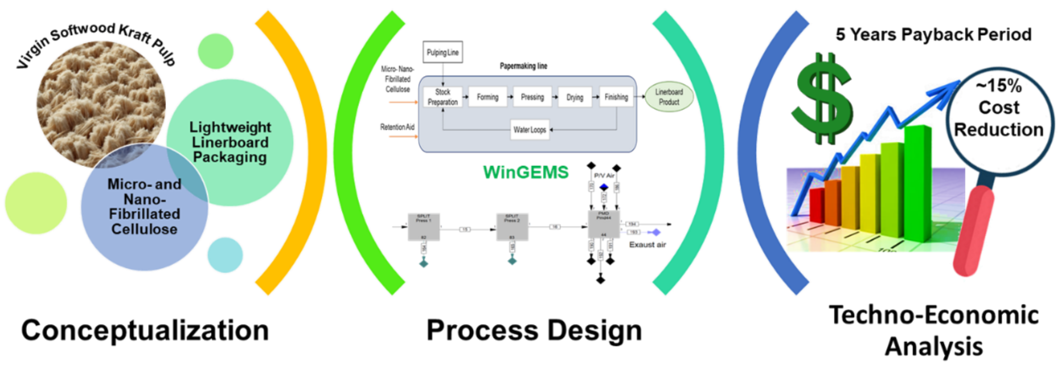
GRAPHICAL ABSTRACT



Techno-Economic Analysis of Lignin-Containing Micro- and Nano-Fibrillated Cellulose for Lightweight Linerboard Packaging

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A key challenge for the paper industry in adopting nanocellulose materials is finding the right balance between production costs and the performance benefits for specific paper grades, given the industry's variety of products and processes. This study developed the first model to evaluate changes in steam consumption and other process parameters on a paper machine when incorporating lignin-containing micro- and nano-fibrillated cellulose (LMNFC) as a dry-strength additive, as well as its economic implications. Significant operational differences were observed in steam consumption, dissolved solids in the sewer stream, and production rates when implementing LMNFC in different scenarios. Using the assumption that reductions in basis weight frees up enough drying capacity to offset the additional drying requirements of LMNFC, this led to a 15% reduction in manufacturing costs while maintaining paper strength. A capital payback period of five years was estimated for LMNFC production, with a minimum selling price of $243 per ton of linerboard. It is important to evaluate both process dynamics and dual cost metrics (cost per ton and cost per area), when analyzing the impact of LMNFC on paper and board production. While LMNFC increases the cost per ton, the lower cost per square feet underscores its material efficiency and economic benefits, particularly for lightweight grades.

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Keywords: Techno-economics; Nanocellulose; Refining; Cationic starch; Drainage; Lightweight packaging

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INTRODUCTION

Among the different emerging papermaking additives with better efficiency and more sustainability, micro-/nano-fibrillated cellulose (MNFC) is highlighted as a novel, effective dry-strength agent for various paper grades, particularly in linerboard packaging paper (Bharimalla *et al.* 2017; Rice *et al.* 2018; Starkey *et al.* 2021; Taipale *et al.* 2010; Zambrano *et al.* 2020; Arafat *et al*. 2025). The addition of lignin-containing micro-/nano-fibrillated cellulose (LMNFC) can be a cost effective strategy to improve strength properties or reduce the fiber consumption in paper applications (Starkey *et al.* 2021). The strength gains achievable with either MNFC or LMNFC addition depends on its degree of fibrillation, the amount added, and the level of refining on the base stock (Zambrano *et al.* 2020), but as fibrillation, addition rates, and refining increase, the draining ability of the free-water decreases (Hubbe and Heitmann 2007; Starkey *et al.* 2021). Lower rates of drainage negatively affect paper machine performance and operating efficiency by reducing the solids content entering the press. Traditionally, paper machines are slowed down to allow for more drainage on the forming wire and to keep a higher level of solids entering the press and subsequently the dryer sections (McDonald and Kerekes 2017).

Since LMNFC has a higher water retention value than traditional papermaking fibers, its effect on furnish dewatering is one of the main barriers to wide-scale industrial adoption (Hubbe *et al.* 2017; Lindstrom 2019; Lindström *et al.* 2015). A study by Starkey *et al.* (2021) shows that the negative effects on drainage can be minimized by reducing basis weight or eliminating refining in the absence of any retention and drainage aids without sacrificing burst and compression strength. It was found that forming a 150 gsm handsheet with no LMNFC had a drainage time of 9.5 seconds. Reducing the basis weight to 125 gsm and adding 2% LMNFC resulted in a drainage time of 10.4 seconds. Numerous studies have discussed how wet-end chemistry programs can be adjusted to offset the adverse effects of LMNFC on dewatering (Taipale *et al.* 2010). Between minimizing the impact on drainage by lightweighting the sheet and then optimizing the wet end chemical program, it is possible to offset the higher drainage times typically associated with nanocellulose. Yet, the concerns about whether this is an economically practical solution remain.

There have been several efforts to model the paper machine drying process using MATLAB (Kong *et al.* 2016; Kong and Liu 2012; Zhang *et al.* 2018). Some of the key findings were that the basis weight of the sheet has a more significant impact on how much drying energy is required than the energy associated with increasing machine speed, *e.g.*, the energy consumption of drives, auxiliary fans, and pumps (Kong and Liu 2012). Since these models were static mass and energy balances of the process, they were unable to account for the interdependence of the papermaking process. Paper mills are highly interconnected; therefore, minor changes in one process stream can significantly affect the rest of the process (Barrios *et al.* 2023; González *et al.* 2025). Thus, software that is capable of processing dynamic information is required to build a model that is more representative of a continuous process.

WinGEMS is a software developed specifically for the paper industry to overcome the limitations of static process modeling (Valmet 2015). In addition to the capability to model dynamic processes, it has built-in calculations specific to papermaking operations. WinGEMS allows users to evaluate process changes and potential capital investments by understanding how all parts of the process will respond. For example, the dryer section is one of the key operation areas that influence the energy balance in the process. The dryer consumes energy in the form of medium-to-low-pressure steam, *e.g.*, 60 to 160 psi, to dry paper from approximately 40 to 45% solids to at least 90% solids. This level of energy consumption has a significant impact on a mill's cost position (Bajpai 2018). Steam pressure used in the dryer section is just one of hundreds of process variables that affect a machine's operating performance. Other variables include, but are not limited to, the type of chemical additives and their addition rates, vacuum box pressure, machine speed, press nip type and dwell time, solids content in the headbox, the degree of fiber fibrillation, and first pass retention.

This study developed a WinGEMS model of a paper machine to evaluate the incorporation of LMNFC to produce linerboard for packaging applications. The model was built using lab-scale data reported by Starkey *et al*. (2021). Mass and energy balances were calculated using the outputs of the WinGEMS model to determine the effects of LMNFC addition on manufacturing costs, payback period, and the minimum selling price of linerboard. This study elucidates the production impacts of integrating LMNFC into the furnish, and the results support the economic viability of converting linerboard production lines from producing heavyweight grades to prioritizing lightweight grades offering paper mills a practical pathway to implement a sustainable cellulose-based papermaking additive.

MATERIALS AND METHODS

Process Description

WinGEMS simulation software was used to develop a comprehensive mass and energy balance of a paper production line, primarily consisting of the paper machine and its associated operational units, as illustrated in Fig. 1. The model was based on an integrated mill producing linerboard for packaging applications; however, the pulp mill was outside the scope of this analysis and not included in the model. Key machine parameters were determined from metrics reported in the FisherSolve™ database. Paper Machine Performance Guidelines for linerboard paper grade and confirmed through informal conversations with industry partners (TAPPI 2022; ResourceWise 2023).

The modeled paper machine consists of a singly-ply fourdrinier former with short and long white water circulation systems (Smook 2016). It is assumed that the operation of the machine is limited by steam availability in the dryer section, and the machine drives have the capacity for increased production speeds. These constraints were incorporated to represent a realistic operational scenario for evaluating the impact of LMNFC. If adapting the model to a specific machine, these assumptions should be adjusted to reflect that specific machine's limitations. Additionally, to simplify the analysis, the only chemical additive in the model was cationic starch, which functions as a retention aid for fibers and LMNFC (Garland *et al.* 2022). Details of the parameters for each operational unit are listed in Tables 1, 2, and 3.

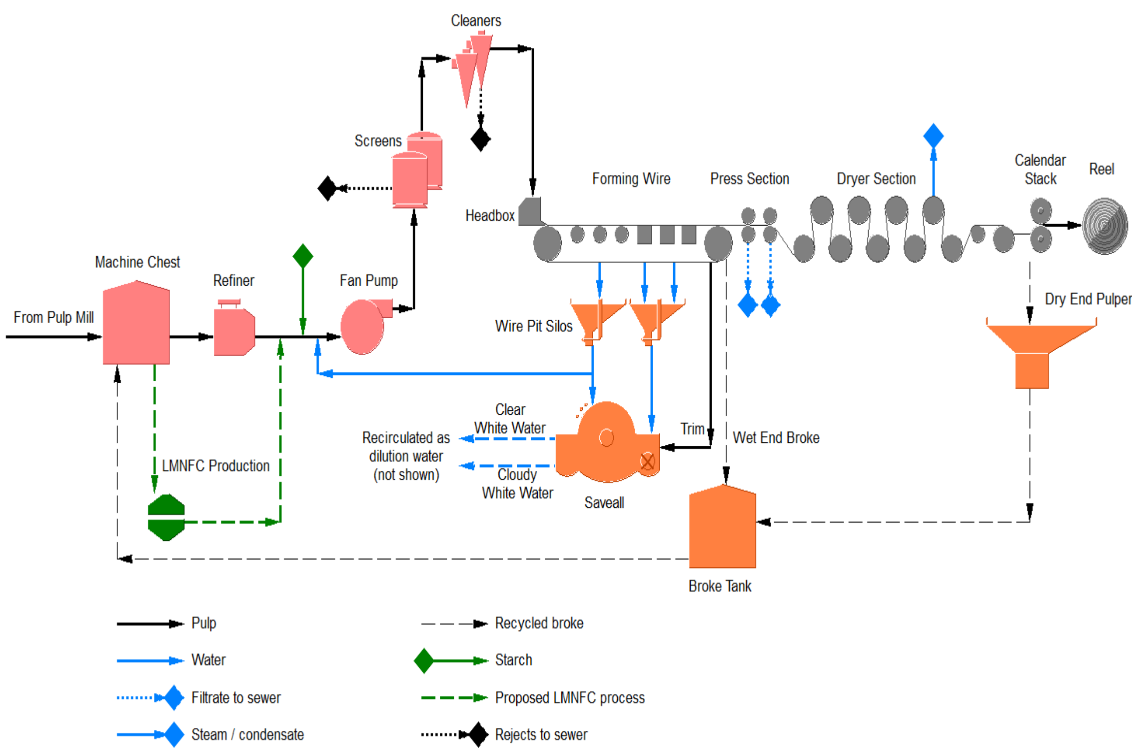

Fig. 1. Flow diagram of the papermaking process with the proposed addition of LMNFC production. to keep the diagram simple, the full white water recirculation loop is not illustrated and specified in Table 2.

Table 1. Model Input and Process Parameters for Pulp Fiber and Starch

Pulp Fiber Stream Inputs	
Parameter Description	**Value**
Softwood flow	90.7 t/h
Consistency	12%
Suspended solids component	100% pulp
Temperature	100 °F
Solids Content of Fiber Streams	
Process Stream Description	**Solids Content (%)**
Machine chest feed (all fiber input streams)	3.50
Refiner feed	3.50
Secondary cleaner feed	0.33
Sheet after foils	3.00
Sheet after suction boxes	12.00
Sheet after couch roll	20.00
Sheet after first press	35.00
Sheet after second press	45.00
Sheet after dryers	94.00
Save all fiber mat	11.00
Starch Addition	
Parameter Description	**Addition Rate (%, relative to oven dried pulp)**
With no LMNFC	1.5
With LMNFC	0.8
Other Model Parameters	
Parameter Description	**Value**
Seal pit and silo temperature	122 °F
Refiner pulp loss to dissolved wood solids	0.20%
Pulp loss to dissolved wood solids during LMNFC production	0.20%

Table 2. Process Water Flow Rates

Process Stream Source	**Process Stream**	**Flow Rate (t/hr)**
Cloudy white-water chest	Refiner dilution	380
	Silo white water to fan pump (excess to save all)	11,700
Clear white-water chest	Secondary cleaner dilution	1,300
	Thick stock dilution	742 (dilution control to 3.5% solids)
	Broke dilution	200 (dilution control to 3.5% solids)
Freshwater addition at 80 °F	Headbox showers	72
	Breast roll shower	58
	Wire showers	225
	Trim showers	4.5
	Total freshwater (excess to Sewer)	700

Table 3. Operational Parameters of the Paper Machine Dryer Section

Parameter Description	Values
Outlet Sheet Temperature	176 °F
Outlet Sheet Solids	99%
Heat Loss	5%
Pressure Drop	5 psia
Exhaust Air Temperature	190 °F
Blow Through Steam	5%
Steam Vent to Atmosphere	5%
Dryer Steam	60 psig, 307 °F
Air Ventilation Properties	flow rate: 50% of exhaust air
	0 psig, 170 °F
	1.0% mass water vapor
	99.0% mass air
	0.01 H_2O/dry abs. humidity
	Dew point temperature 76.9 °F
	Wet bulb temperature 82.2 °F
Tramp Air Properties	flow rate: back calculated
	0 psig, 90 °F
	1.0% mass water vapor
	99.0% mass air
	0.01 H_2O/dry abs. humidity
	Dew point temperature 53.6 °F
	Wet bulb temperature 67.2 °F

Model Parameters

Paper machine

The fiber input in the model is a high-lignin-content, virgin softwood kraft pulp. In the U.S., 53 out of 87 linerboard machines used at least 65% virgin fiber in their product (from ResourceWise as reported in Starkey 2022). To simplify the analysis and minimize the assumptions, the model assumes 100% virgin softwood kraft pulp. The input stream is the pulp coming out of the mill's high-density chest at 12% solids. In the base case (Scenario 0), all the fiber entering the process is used to produce linerboard minus the fiber yield loss. In the alternate cases, a part of the incoming fiber stream is split off the incoming feedstock and processed into LMNFC prior to mixing back into the furnish.

LMNFC production

The LMNFC production line is based on the "co-located on-demand" refiner process reported by Abbati de Assis *et al.* (2018). The mechanical energy required to produce LMNFC is based on the values reported by Starkey *et al.* (2021), who achieved low levels of fibrillation using 3,000 KWh/t. While Starkey *et al.* (2021) used a Masuko grinder for lab-scale LMNFC production, Valmet has developed an industrial-scale process based using a traditional pulp refiner equipped with specialized refiner plates to promote fibrillation (Cowles *et al.* 2023). It is assumed that the two processes have comparable net energy requirements for LMNFC production.

The capacity of the co-located LMNFC production process is 50 t/day, providing an excess of LMNFC beyond the needs of a single paper machine. This excess capacity can supply LMNFC to additional production lines within the mill. Figure 2 depicts the WinGEMS model of the LMNFC production. A control function, used in conjunction with a SPLIT block (see Block 22 in Fig. 2), calculates the amount of pulp required to produce LMNFC at a 2% addition rate. The control function also accounts for fiber losses during the fibrillation process as dissolved wood solids. LMNFC production exceeding the demand for the paper machine was not included in the simulation.

Cloudy white water was diverted from the refiner dilution block and used to dilute the thick stock from 12% to 1.5% solids prior to LMNFC production. Mechanical fibrillation of the softwood fibers into LMNFC was simulated using the REACTION block. WinGEMS does not provide information about the degree of fibrillation of fiber refining. To track the LMNFC as a separate component from the fiber through the rest of the process, the REACTION block was set up to move the incoming pulp stream component into a LMNFC stream component. The use of a separate component stream for LMNFC followed the same convention of using dedicated component streams for other process additives such as calcium carbonate, starch, wet-strength additives, and retention aids. The reaction block was set up to move 99.8% of the incoming pulp component in stream 61 to the LMNFC stream component (in stream 91), and the remaining 0.2% of the incoming pulp was moved to the dissolved organics stream component (in stream 91). The amount of energy used per ton of fiber for fibrillation is manually entered into the REACTION block, and the total energy used for fibrillation is calculated and reported in the model output.

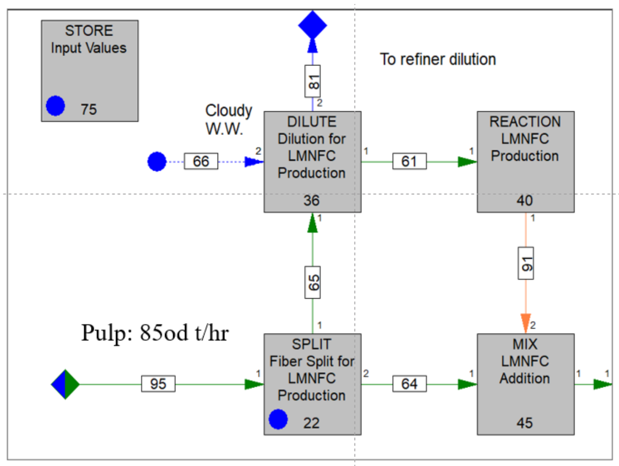

Fig. 2. WinGEMS model of LMNFC production. LMNFC is produced via mechanical fibrillation and is modeled like a refiner

Techno-Economic Analysis

Scenarios descriptions

In addition to the base case (Scenario 0), the developed model was used to investigate three alternative cases (Scenarios 1 to 3). The differences between each scenario are reported in Table 4. In Scenario 0, a 150 GSM linerboard product is simulated with 1.5% cationic starch addition and no LMNFC addition.

Numerous studies have discussed how wet-end chemistry programs can be adjusted to offset the negative effects of LMNFC on dewatering (Taipale *et al*. 2010). Additionally, a study by Starkey *et al.* (2021) shows the negative effects on drainage can be offset through the reduction of basis weight or refining without reductions in burst strength and short span compression. This study was conducted without the use of retention or drainage aids, and it is assumed that addition would further minimize the effects LMNFC has on drainage. So the scenarios evaluate the effects of eliminating refining (Scenario 1) and the combination of offsetting a lower basis weight and starch addition with the use of LMNFC (Scenario 3). Scenario 2 uses a lower basis weight than Scenario 0 to establish a benchmark for the lower basis weight used for Scenario 3**.**

The techno-economic model applied here relies on several conservative assumptions to translate laboratory-scale findings to scaled process conditions. Retention assumptions are derived from experimental data, early-stage pilot trials, and existing literature. Specifically, the model assumes that LMNFC retention resembles pulp fiber retention during stock preparation and starch retention on the paper machine, consistent with the combined LMNFC–starch retention effects reported by Hubbe (2019). Table 5 outlines the retention rates for fiber, LMNFC, and starch.

The production rate remains constant across scenarios by leveraging lighter-weight sheets achieved by adding LMNFC, which helps mitigate potential dewatering issues, as lower grammages generally improve dewatering (Hubbe and Heitmann 2007; Hubbe *et al.* 2020; Paulapuro 2001; Rantanen and Maloney 2013; Barrios *et al.* 2023). The basis weight reduction is supported by findings from Starkey *et al.* (2021) and other literature that report strength enhancements from MNFC additions in virgin fibers (Bharimalla *et al.* 2017; Ghasemian *et al.* 2012; Rice *et al.* 2018). Reducing basis weight in linerboard products is feasible if fiber bonding properties are enhanced. Starch-derived products, in addition to MNFC, are known to improve bonding properties (Hubbe 2014, 2019). Additionally, studies have shown improved performance of MNFC addition to starch, suggesting that even lower amounts of starch can increase or maintain strength properties (Ghasemian *et al.* 2012; Rice *et al.* 2018), supporting the assumptions in the model.

Table 4. Process Scenarios Simulated in WinGEMS to Evaluate the Impact of LMNFC on Linerboard Production for Packaging Applications

Variable	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Basis weight (GSM)	150	150	125	125
LMNFC Addition (wt. %)	0	2	0	2
Refining Energy (hp-day)	5	0	5	5
LMNFC Fibrillation Energy (MWh/t)	--	3.2	--	3.2
Starch Addition (%)	1.5	0.8	1.5	0.8
Starch Addition (lb/t)	30	16	30	16

Table 5. Mass Split Inputs and Retention Rates for Pulp, LMNFC, and Starch in the Papermaking Process for Scenarios 0 to 3 in Linerboard Production

Process Location	Pulp (%)	LMNFC (%)	Starch (%)
Primary cleaner accepts	90	90	90
Secondary cleaner accepts	99	99	99
Screen rejects	0.14	0.42	0.42
Trim at couch roll	5	5	5
Wet end broke after couch roll	5	5	5
Dry end broke and winder losses after dryers	5	5	5
Foils	74	50	50
Suction Boxes	97	80	80
Couch Roll	99.5	94	94
First Press	100	99	99
Second Press	100	99	99

Sensitivity analysis – Impact of drainage

For scenario 3, a sensitivity analysis on manufacturing cost was carried out by varying the solids content entering the dryer section by ± 2%. The solids content was adjusted in the WinGEMS model, and the results of the converged model were exported to Excel for analysis. The detailed parameters for the sensitivity analysis are listed in Table 6. The goal of this analysis was to account for uncertainties on how LMNFC impacts dewatering. While the lab results presented in Starkey *et al*. (2021) show that the decrease in basis weight offsets the increase in drainage time from LMNFC addition, it should be noted when scaling to larger scale production, that the general trends seen in the lab work will still apply, but the magnitude of change will differ. In the absence of corresponding pilot scale data on drainage, the sensitivity analysis is used to determine significance of the impact.

Table 6. Progression of Water Removal on the Paper Machine for Conducting Sensitivity Analysis to Evaluate the Effect of Solids Entering the Dryer in Scenario 3

Inputs	Low Water Removal	Scenario 3	High Water Removal
Headbox solids content, %	0.5	0.5	0.5
Table solids content, %	12	12	12
Couch solids content, %	18	19	22
Solids after 1st press, %	33	35	37
Solids after 2nd press, %	43	45	47
Solids after dryers, %	99	99	99

Financial Assumptions for Estimating the Minimum Selling Price (MSP)

The capital investment for installing LMNFC production line to a pre-existing linerboard machine was determined in a techno-economic analysis framework published by Abbati de Assis *et al.* (2018). Using this framework as a starting point, Starkey *et al.* (2021) calculated the manufacturing cost of LMNFC with a relatively low fibrillation level to be $752/t, excluding post-manufacturing treatment and processing. Taking into account the capital expenses, the minimum selling price of the LMNFC is $916/t to overcome a 16% hurdle rate (Starkey *et al.* 2021). This minimum selling price is based on a production facility selling the LMNFC rather than using it as a process additive. Other raw materials and utility costs for the economic analysis are listed in Table 7.

Incremental costs in energy, freshwater, starch, pulp, and LMNFC to produce the linerboard in each scenario were determined. The square footage production rates were also calculated using the equations provided by Starkey *et al.* (2021). Manufacturing costs were assessed relative to Scenario 0, and the cost comparison was simplified by only incorporating the changing material and utility flows.

The model results from Scenario 3 were used to update the original techno-economic analysis completed by Abbati de Assis *et al.* (2018). A revised payback period for the LMNFC production line was calculated based on a 16% internal rate of return to determine the minimum product selling price for the lightweighted linerboard.

Table 7. Raw Materials and Utility Costs for Estimating the Minimum Selling Price of Linerboard Paper Grade with LMNFC as a Dry-End Additive

Item	Unit	Value	References
Pulp	USD/t	199	(ResourceWise 2023)
LMNFC	USD/t	752	(Starkey et al. 2021)
Starch	USD/t	134	(Abbati de Assis et al. 2018)
Energy	USD/MWh	72	(Abbati de Assis et al. 2018)
Steam	USD/t	10	(Abbati de Assis et al. 2018)
Paper Product	USD/MSF	150	(Fastmarkets 2024)
Fresh Water	USD/t	0.66	(Abbati de Assis et al. 2018)

RESULTS AND DISCUSSION

Table 8 presents the model results for the significant process streams. All values were reported with either 2 or 3 significant figures. Steam consumption varied slightly between scenarios, staying within 5% of the base case (Scenario 0), and was considered an insignificant difference. In Scenario 1 there was a significant decrease in the dissolved wood solids found in the wastewater stream going to the sewer. This reduction comes from eliminating refining of the main paper furnish with the addition of LMNFC. Reduced dissolved wood solids going to the sewer reduces the amount of downstream processing required in the wastewater treatment plant before discharging it into a river. As environmental regulations become stricter on emission targets, mills could leverage the use of LMNFC to maintain compliance. Despite Scenario 1 increasing production costs per MSF by ~3%, further studies can be done to determine the optimal amount of refining and LMNFC addition, *i.e.*, the furnish could be partially refined with less LMNFC addition to minimize dissolved wood generation without increasing costs.

Another significant difference is that even though all scenarios produce the same tonnage of paper, the lighter grade (125 GSM) generates 78 MSF/ton compared to 65 MSF/ton for the heavier grade (150 GSM). The variation of metric square footage becomes important since market dynamics significantly influence cost variations, as some paper grades are priced more competitively per ton, and others align better with a per-area metric (Fastmarkets 2024). Linerboard, for example, can be priced and sold by the thousand square feet (MSF) rather than by weight (Fox *et al.* 2023). In this sense, using LMNFC to lightweight the sheet allows for significantly more square footage per ton of material, leading to a lower cost per MSF and a ~15% reduction of manufacturing costs compared to the base case.

In contrast, manufacturing cost on a tonnage basis increases from 218 to 229 USD/t (Table 9). Customer preferences and industry standards for specific grades often favor one pricing method, which can vary based on the manufacturing facility and the cost position they prioritize. Therefore, presenting both cost per ton and cost per MSF provides a holistic view of the operational and economic impacts of LMNFC addition.

Table 8. Key Output Parameters from the Mass and Energy Balance of the Papermaking Process for Baseline (Scenario 0) and Alternative Scenarios (1 to 3) in Linerboard Production for Packaging Applications

Output	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Paper Production (O.D. t/hr)	84.8	84.4	84.8	84.2
Pulp Yield (%)	99.6	98.8	98.8	98.8
LMNFC Yield (%)	--	96.0	--	96.0
Paper Composition (Fiber/LMNFC/Starch %)	97.6/--/1.4	96.4/1.9/0.7	97.6/--/1.4	96.4/1.9/0.7
Steam Use, Dryers (lb/hr)	299,710	298,300[1]	299,710[1]	297,540[1]
Steam Use, Silos (lb/hr)	75,381	75,368[1]	75,381[1]	75,360[1]
Sewer Flow (t/hr)	1,393	1,411[1]	1,393[1]	1,310
Dissolved Solids, Sewer Flow (t/hr)	22.3	0.3	--	22.6[1]

[1]less than 0.5% difference so it was not a significant change

Table 9. Calculated Manufacturing Costs (USD) for Each Scenario Assuming a Basis of 1 hour, and the Change in Total Cost / MSF Compared to the Base Case (Scenario 0).

Output	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Paper Production (MSF)	5,512	5,486	6,614	6,568
Fiber Cost	16,476	16,197	16,476	16,156
LMNFC Cost (includes the energy to produce)	-	1,206	-	1,203
Steam Cost, Dryers	1,499	1,492	1,499	1,488
Steam Cost, Silos	377	377	377	377
Starch	159	79	159	79
Total cost/hr	18,511	19,351	18,511	19,303
Total cost / t	218	229	218	229
Total cost / MSF	3.4	3.5	2.8	2.9
Change in Total cost/ MSF (compared to Scenario 0)	--	2.9%	-17.6%	-14.7%

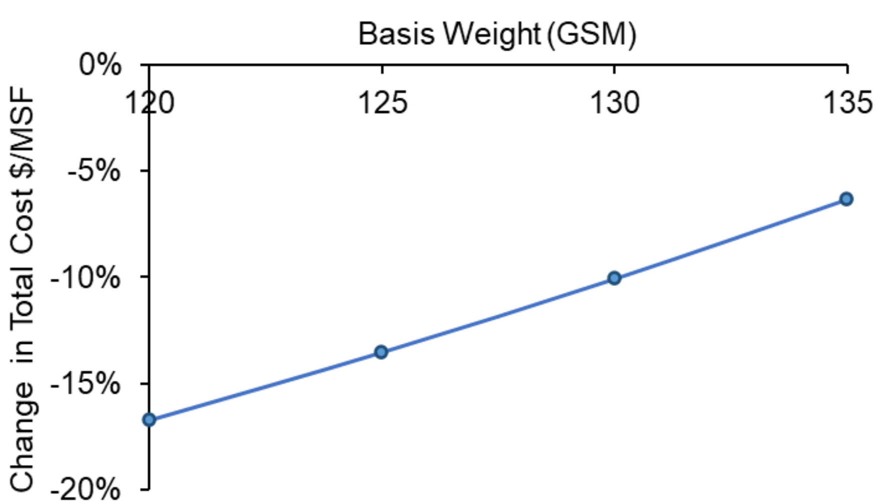

Fig. 3. Sensitivity analysis for Scenario 3 with varied basis weights to show how the obtained basis weight reduction changes the total production cost/msf for Scenario 0.

The payback period for Scenario 3 was calculated by inputting the cost data into the TEA/capital investment model with a 16% hurdle rate. The analysis estimated a 5-year payback period for the LMNFC production line, which is often considered a desirable timeframe for most investments (Kagan *et al.* 2024). Moreover, the minimum selling price required for the lightweight sheet, which maintains the same strength properties as the heavier sheet, was determined to be \$243/ton linerboard. This selling price reflects the balance between material savings achieved through basis weight reduction, the additional costs associated with LMNFC production, and incorporation of LMNFC into the linerboard.

The sensitivity analysis in Fig. 3 shows that changes in basis weight impact the total cost per MSF. For example, a moderate reduction in basis weight from 150 gsm to 135 gsm results in a 6% decrease in production costs per MSF (approximately \$3.2/MSF), which corresponds to a \$230 per ton and a slightly increased MSP of \$244/ton. Therefore, the implementation of LMNFC in linerboard production can be economically attractive, even with a 10% reduction in basis weight.

In summary, adding 2% LMNFC to the fiber furnish reduces the total amount of fiber per square unit area while maintaining strength properties, leading to a manufacturing cost reduction of ~15%. This demonstrates the economic advantage of incorporating LMNFC into linerboard to produce lightweight grades. This approach lowers fiber costs, increases production efficiency, and potentially generates revenue by delivering more square footage per ton of raw materials. In future work, a more detailed analysis should include operational and financial risk analysis, such as the sensitivity to major assumptions, currency fluctuations, or changes in interest rates.

CONCLUSIONS

This study elucidated the production impacts of integrating lignin-containing LMNFC into the papermaking furnish. The results support the economic viability of converting linerboard production lines from heavyweight to lightweight grades, offering paper mills a practical pathway to implement a sustainable, cellulose-based papermaking additive. A WinGEMS process model was developed to evaluate changes in paper machine economics when LMNFC was utilized as a dry-strength additive. The model is based on a state-of-the-art linerboard papermaking process capable of producing 85 oven-dry tons per hour. In the base case, a 150 grams per square meter (GSM) linerboard is produced using 1.5% cationic starch as a retention aid without LMNFC. In the alternative case, 2% LMNFC is added, and the cationic starch addition is reduced to 0.8%, resulting in the production of a 125 GSM linerboard with the same strength profile as the 150 GSM linerboard. The 17% reduction in basis weight corresponds to a 15% cost reduction when accounting for incremental fiber and manufacturing costs per MSF. In another scenario, LMNFC is used to eliminate refining instead of reducing the basis weight. While eliminating refining increases manufacturing costs by 3%, it significantly reduces the amount of dissolved wood solids discharged to the sewer from 22 to 0.3 tons per hour. This reduction in dissolved wood solids could have a positive impact on the mill's environmental footprint while also lowering water treatment processing requirements. The payback analysis reinforces the scalability of LMNFC adoption and helps manufacturers to justify capital investment by improving production efficiency, reducing fiber usage, and the potential revenue gains from a higher square footage output.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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