Decision-making process for the identification of preferred lignin-based biorefinery strategies

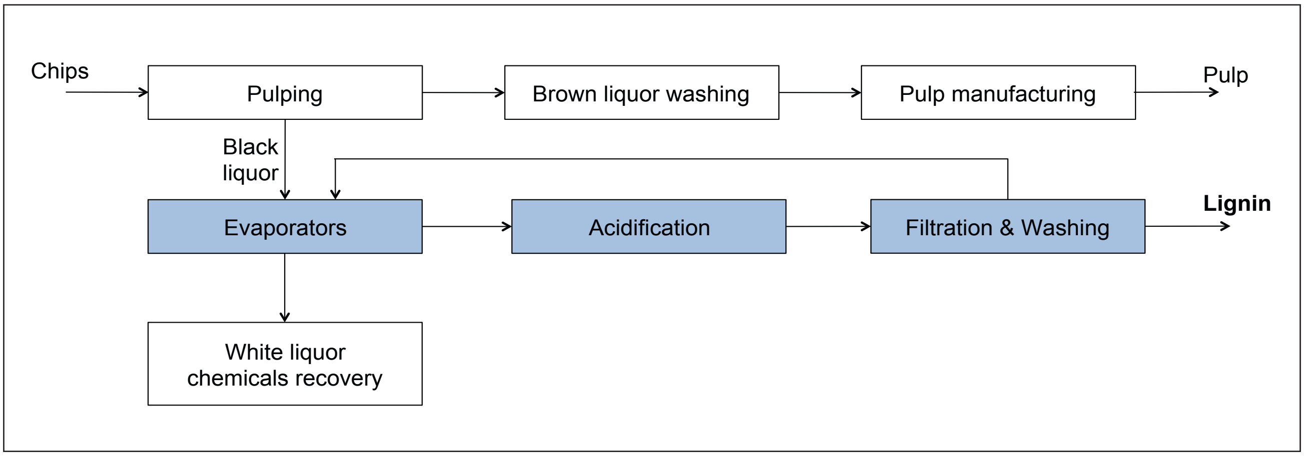
CÉDRIC DIFFO TÉGUIA, SOPHIE D'AMOURS, ROD ALBERS, AND PAUL STUART

ABSTRACT: The lignin biorefinery is emerging; there has been significant progress in recent years regarding lignin extraction and conversion processes, their implementation at the commercial scale, and the validation of lignin substitution potential in various applications. In this paper, seven strategies for implementing the lignin-based biorefinery into a kraft pulp mill were considered, and different performance metrics for these strategies were calculated in order to identify the "most preferred". The different options addressed two distinctly different objectives that companies can consider regarding their biorefinery strategy, either (1) a near-term mill-level profitability improvement vision, or (2) a longer-term revenue growth-oriented vision. A phased-implementation approach was systematically defined for each option in order to mitigate technology and market risks. Lignin product applications that were considered included phenol replacement in phenol-formaldehyde (PF) resins, polyols replacement in polyurethane (PU) foams, and polyacrylonitrile (PAN) replacement in carbon fiber.

A Multi-Criteria Decision-Making (MCDM) panel was executed for evaluating the seven lignin-based biorefinery strategies, using a set of economic, market risk, and competitiveness criteria. Although the panel selected Internal Rate of Return (IRR) as the most important criterion, Competitiveness on Production Costs (CPC) appeared to be the most important factor for distinguishing between lignin strategy options. CPC reflects the robustness of the biorefinery strategy relative to an aggressive price-cutting strategy from the competition. Overall, strategies involving lignin precipitation were more attractive economically, while those involving larger-scale solvent pulping processes and the associated larger revenue streams were considered better long-term strategies. The most preferred strategy considered by the panel was for precipitated lignin sold for both PF resin and PU foam applications. The next preferred strategy considered lignin sales to the same market segments, but at larger volumes. The next closely-ranked strategy considered the production of a lignin-based PF resin at the host mill. These three strategies were identified as "preferred," for further, more detailed assessment.

Application: This paper provides an evaluation of lignin-based biorefinery strategies in the context of retrofit implementation within a market kraft pulp mill. The evaluation is made though a Multi-Criteria Decision-Making panel, whose members considered a set of profitability, market, and risk-based criteria.

Lignin is burnt as black liquor in the recovery boiler to produce steam and electricity for the pulp manufacturing process, but it could also be separated and comprise the feedstock for new "green" revenue streams. Although the lignin chemical structure is dominated by aromatics and methoxyl groups, it also includes a variety of other functional units, which makes it potentially valuable in a wide range of applications [1,2]. Recent progress in lignin extraction from black liquor has resulted in the emergence of the first commercial plants in the United States, Canada, and Sweden, using either the LignoBoost process [3] or the LignoForce process [4]. Both of these processes are based on the use of carbon dioxide to lower the black liquor pH to 9-10, and causing lignin to precipitate [5,6]. **Fig. 1** illustrates operational steps of a generic lignin precipitation process. Alternatively, lignin can be extracted directly from wood through various biomass fractionation processes [7], as generically illustrated in **Fig. 2**. A solvent-based technology can be employed for that purpose, which has a less damaging effect on the lignin structure compared to the kraft pulping process. The cases of lignin precipitation units integrated within an existing kraft-pulping mill and of lignin extraction within a stand-alone organosolv plant have been systematically treated by Diffo Téguia et al. from a techno-economic perspective [8]; nevertheless, extracting and/or producing lignin is only the first step of a successful biorefinery transformation. Companies face the complex choice of identifying the right applications to which they should sell their lignin, knowing that each option implies unique technical and market challenges, while the precise understanding of the linkage between lignin properties, derivative product performance, and



1. Simplified lignin precipitation process from black liquor.

market supply/demand growth remains uncertain.

Considering this context, this paper aims to assess different strategies for the deployment of the lignin-based biorefinery. Risk mitigation using a phased implementation approach is considered, taking into consideration technology and market uncertainties associated with the business model. The following objectives were addressed in this project:

1. Generalize the market and technology landscape associated with the conversion of lignin into added-value derivatives.
2. Define a set of lignin-based biorefinery strategies, potentially suitable for implementation within an existing kraft pulp mill.
3. Define a set of technology, market and risk-based criteria, and consider these in a panel methodology, in order to identify the "most preferred" lignin-based biorefinery strategies.

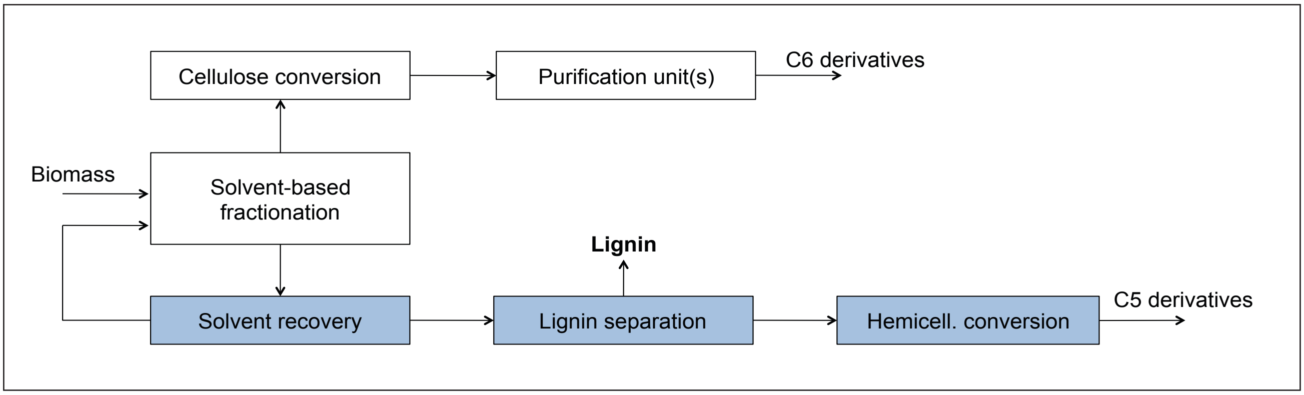
LIGNIN DERIVATIVES AND MARKET APPLICATIONS

The spectrum of products that can potentially be synthesized from lignin is fairly diversified. Holladay et al. [9] generally described this spectrum as including power, fuel, and syngas products, macromolecules, and aromatics, which can further be classified as near-term, medium-term, and long-term opportunities.

Lignosulfonates obtained from the sulfite pulping process are the most widely used today among technical lignin types; for example, they are used as concrete and animal feed additives, for dust control, or as a precursor in the production of vanillin, dimethyl sulfide (DMS), and dimethyl sulfoxide (DMSO). Phenol-formaldehyde (PF) resins, polyurethane (PU) foams, and carbon fibers are emerging as promising near-term opportunities for kraft and organosolv lignins [10-12], the category of lignins considered in this paper. For example, lignin can theoretically replace more than 50% of phenol used in resin formulations [13]; however, high levels of substitution are not recommended yet due to the lower performance of the resulting resin (bond strength, hardening time, mechanical properties of panels) [14]. In practice, at the present time the substitution potential of essentially unmodified lignin in PF resins is limited to 25%, and it can increase to 40% if the lignin is pre-treated, as by phenolation prior to resin manufacturing, for example [15].

With regards to PU foams manufacturing, lignin can be used as a replacement of polyols and is more suitable for rigid foams applications. Lignin depolymerization to obtain polyols can be realized with high yields (80%-90%) but this process remains embryonic for the moment [16]. A level of substitution of 15% has been achieved using a mechanically ground lignin (without chemical modification), while chemically modified lignin can replace up to 30% of polyols in PU foams [12], achieved through an oxyalkylation process.

The opportunity to produce carbon fiber from lignin is arguably one of the most attractive potential applications. Carbon fiber exhibits unique physical and mechanical properties that make it suitable for replacing metals in various applications, including in the automobile and aerospace industries [17]. Despite growing demand, carbon fiber production volumes remain low due to its high cost, which is related in good part to the cost of precursors. Lignin can potentially be a much cheaper alternative to polyacrylonitrile (PAN), which is currently the most common precursor used in the industry [18]. The conventional carbon fiber manufacturing process includes four steps: fiber spinning, stabilization, carbonization, and surface treatment. The lignin substitution potential varies with the type of spinning employed, ranging from 50% in the case of wet spinning to a full replacement when melt spinning is used [19]. Past studies have highlighted some difficulties for the spinning step using softwood kraft lignin, which charred at high temperature. Recent developments have overcome that limitation by separating the black liquor into distinct molecular weight fractions using an ultrafiltration membrane prior to lignin precipitation and using only the low-molecular weight fraction as a carbon fiber precursor [20]. Nevertheless, the current performance of lignin-based carbon fibers are not yet equivalent to PAN-based ones, especially for high-strength applications [17].



2. Simplified solvent-based biomass fractionation process.

MITIGATING BIOREFINERY RISKS THROUGH PHASED IMPLEMENTATION

Despite risks associated with lignin product performance and market growth, several forest product companies seek to have significant strategic advantages to being first- or early-to-market with the manufacture of lignin. A practical approach to mitigating these risks is through phased implementation. Chambost et al. [21] suggest a nominal three-phase approach.

Various factors influence the definition of phases from the perspective of mitigating risk, including (1) the product point-of-entry on the existing value chain, (2) the market characteristics and associated penetration needed, and (3) the technology development approach for the deployment of the strategy [22]. For the example of lignin use in phenolic resin applications, the first factor would consider whether lignin is sold as phenol replacement for resin manufacture, or whether it is mixed/converted into the PF resin. The penetration rate for a given position on the value chain, which is dependent on the substitution potential, leads to defining the design capacity of the process over several phases. Will the lignin be sold internally, or sold and re-purchased from the PF resin supplier? The third element considers whether the company is open to horizontal or vertical integration. Is the company open to vertical integration, as well as increasing risk and added value from manufacture of the downstream phenolic resin, requiring that their strategy brings them closer to the final user? What would be the company's competitive position to achieve this goal, relative to others?

EVALUATION AND SELECTION OF BIOREFINERY OPTIONS

The problem of biorefinery strategy selection has been addressed in various studies, and several methods have been developed to address the evaluation and decision-making regarding individual projects or project portfolios [23-26]. The success of a biorefinery initiative is dependent on a wide range of factors identified using different perspectives, among which the most important must be identified and taken into account during the biorefinery selection process. A committee of decision-makers rather than a single individual is typically responsible for capital investment recommendations in the company, and the committee must respectfully consider a range of technology, market, and risk issues. This emphasizes the need for a decision-making method that is practical for summarizing critical information, and using this to aggregate the perspectives of stakeholders in order to reach a balanced decision. Multi-criteria methods suitable for this purpose have been successfully employed to solve biorefinery decision problems in past studies [27-30]. Among these, multi-criteria decision-making (MCDM) aggregates the panel member preferences systematically and in an interactive context, resulting in an outcome that is readily interpretable, which facilitates alignment between stakeholders regarding "preferred" strategies.

In the MCDM process, the definition of the set of evaluation criteria is critical. Significant care is needed to define important criteria that reflect the values of the company [31]. Criteria can be defined using top-down [32] or bottom-up approaches [33], ultimately resulting in a consistent family of attributes, which should be exhaustive, monotonic, minimal, legible, and operational [34].

OBJECTIVE

This study considers the implementation of a lignin-based biorefinery at a North-American forest product company that owns sawmills and panel board mills, as well as kraft pulp and paper mills. The company seeks to diversify its product offering, starting with one of its market pulp mills. The mill produces 1500 air dried (a.d.) metric tons of kraft softwood pulp per day and is adjacent to a sawmill also owned by the company. Two recovery boilers and one hog fuel boiler are running under normal operating conditions, and the mill has enough cogenerated power to be energy self-sufficient. With regards to the integration of biorefinery processes with the existing pulping process, there is a reasonable capacity for a certain additional steam production, whereas spare capacity at the wastewater treatment plant is more limited. Additional biomass of approximately 1500 bone dry (b.d.) metric tons/day of hardwood saw logs is available as potential feedstock for the biorefinery from the mill-owned forest management area (FMA).

It is assumed that in the base case, a lignin precipitation unit producing 30 b.d. metric tons/day of lignin from black liquor has been implemented at the mill. The objective of the project was to assess the different strategies available to the mill and to maximize the value of the lignin-based biorefinery.

Candidate biorefinery strategies

A preliminary screening of lignin applications was made considering (1) technology and market readiness for different lignin products, and (2) the potential to create competitive advantage in the near and longer terms. This analysis led to retaining polyols replacement in PU foams among immediately achievable alternatives to PF resins applications, while PAN replacement in carbon fibers was retained among the longer-term applications. All strategies were defined as extensions of the Base Case situation, considering phased implementation. The first strategy, referenced as "Ligno 90•PF," aims to improve market position by increasing production volume. It considers tripling the capacity of the lignin precipitation unit from 30 metric tons/day to 90 metric tons/day, still having minimal impact on recovery boiler operations. Two strategy alternatives emerge from this: (1) a mill-centric strategy that focuses on improving the competitive position of the host mill at the current scale (Group 1 strategies), and (2) strategies that seek larger manufacturing scales and greater impact in terms of revenue diversification (Group 2 strategies).

Ligno 90•PF PU and Ligno 90•PF CF strategies consider commercializing lignin for PU foams and carbon fiber applications, respectively. In both cases, 7% of the production would be used in company owned panel board mills, 60% would be sold for PF resin applications, and 33% for either PU foams or carbon fiber applications. A vertical integration approach is represented through the strategy Resin 90, which considers on-site manufacturing of a lignin-phenol-formaldehyde resin. In this case, the acquisition of an existing resin manufacturer is considered in order to facilitate the integration of resin production, as well as access to distribution channels.

In the second group of strategies, a joint venture is considered for the implementation of a standalone solvent pulping plant in parallel to the existing process. It would convert the available supply of hardwood into a portfolio with isobutanol (sold as a biofuel), a hemicellulose-rich sugar syrup (sold as animal feed), and lignin derivatives. The non-lignin products were selected using minimum technology and market risk considerations and remain fixed for all scenarios. The first lignin strategy, Ligno 90 + SP•PF, considers additional sales with the main lignin application. The last two, Ligno 90 + SP•PF PU and Ligno 90 + SP•PF CFs, consider product diversification into PU foams and carbon fiber applications. **Table I** summarizes the Phases for each of the seven strategies.

ANALYSIS METHODOLOGY

Information relative to mass and energy balances for the design of processes associated with the lignin-based biorefinery strategies was collected from the literature. A large-block analysis approach [35] was employed to obtain capital and operating costs estimates for each implementation phase of each strategy.

Techno-economic analysis

Considering retrofit implementation, the specifics of the case study host mill were taken into account for integration potential. This analysis emphasized the materials handling system, the inventory of unused equipment, the energy island and the wastewater treatment plant with the purpose of (1) identifying technology risks and additional costs for their mitigation, as well as (2) the potential for cost reduction resulting from synergies with the existing process.

In order to determine realistic values for capital expenses, capital costs were first estimated considering information in the literature on comparable processes, in a manner consistent with Diffo Téguia et al. [8]. Equipment with similar functions were identified, then data were scaled up to the case study design capacities and actualized using proper cost index factors. Common design heuristics were used to extrapolate components of direct and indirect capital costs for the integrated precipitation units, while the Lang method was employed for the case of standalone solvent pulping plants. Design heuristics were also employed for estimating fixed components of operating costs.

The basis for feed material costs and product prices involved making projections over the period of the project lifetime. Correlations were made between historical feed costs or product prices and energy commodities (crude oil, natural gas, and/or electricity). Average, minimum and maximum values of projections for energy commodities in reports from the International Energy Agency (IEA) [36] and the U.S. Energy Information Administration (EIA) [37] were used to extrapolate to future values for feed materials and products. For materials not directly linked to energy commodities, only historical values were used as the main basis for pricing. **Table II** summarizes feed material unit costs, and **Table III** summarizes product prices considered in this study.

Conservative discounts have been considered for the first three years following the market launch of derivative lignin products. These were nominally set based on the maturity of the targeted applications at: 10% for the replacement of PF resin, 20% for the replacement of phenol and polyols, and 30% for the replacement of PAN. For cash flow calculations, a 1-year construction period was assumed for capacity increase of the precipitation unit and for the solvent pulping demonstration plant, while a 2-year period was assumed for construction of the full-scale solvent pulping plant. In order to compare the impacts of each strategy, cash flow values were actualized to the year of the capacity increase occurring in Phase I of all strategies.

<table>
<tr><th rowspan="2">Strategic Orientation</th><th>Lignin Biorefinery Strategies</th><th>Phase 0
Year 0 – Year 4</th><th>Phase I
Year 5 – Year 9</th><th>Phase II
Year 10 – Year 30</th></tr>
<tr><td>Base Case 30 metric tons/ day lignin precipitation</td><td colspan="3">• Year 0: 100% lignin burnt
• Year 1: 28 metric tons/day burnt, 2 metric tons/day to board mills
• Year 2: 24 metric tons/day burnt, 6 metric tons/day to board mills
• Year 3: 18 metric tons/day burnt, 6 metric tons/day to board mills, 6 metric tons/day to PF resin market
• Year 4: 12 metric tons/day burnt, 6 metric tons/day to board mills, 12 metric tons/day to PF resin market
• Year 5: 6 metric tons/day burnt, 6 metric tons/day to board mills, 18 metric tons/day to PF resin market
• Year 6+: 6 metric tons/day to board mills, 24 metric tons/day to PF resin market</td></tr>
<tr><td rowspan="4">Group 1: Improve mill competitive position</td><td>Ligno 90•PF</td><td rowspan="7">Same as Base Case</td><td colspan="2">Increase of lignin precipitation capacity to 90 metric tons/day
• Year 5: 6 metric tons/day burnt, 6 metric tons/ day to board mills, 48 metric tons/day to PF resin market
• Year 6: 6 metric tons/day to board mills, 84 metric tons/day to PF resin market</td></tr>
<tr><td>Ligno 90• PF PU</td><td colspan="2">Same as Ligno 90•PF, excepting:
• Year 5: 33 metric tons/day to PF resins, 15 metric tons/day to PU foams
• Year 6: 54 metric tons/day to PF resins, 30 metric tons/day to PU foams</td></tr>
<tr><td>Ligno 90•PF CFs</td><td colspan="2">Same as Ligno 90•PF, excepting:
• Year 5: 33 metric tons/day to PF resins, 15 metric tons/day to carbon fibers
• Year 6: 54 metric tons/day to PF resins, 30 metric tons/day to carbon fibers</td></tr>
<tr><td>Resin 90</td><td>Same as Ligno 90•PF</td><td>Acquisition of a resin producer
• Year 10: 290 metric tons/day of resin produced
• Year 11: 435 metric tons/day of resin produced</td></tr>
<tr><td rowspan="3">Group 2: Larger-scale revenue diversification</td><td>Ligno 90 + SP•PF</td><td>Same as Ligno 90•PF + Solvent pulping demo plant[1]</td><td>Increase of solvent pulping to full capacity[2]</td></tr>
<tr><td>Ligno 90 + SP•PF PU</td><td colspan="2">Same as Ligno 90 + SP•PF, excepting lignin distribution: 6 metric tons/day to board mills, 220 metric tons/day to PF resins, 124 metric tons/day to PU foams</td></tr>
<tr><td>Ligno 90 + SP•PF CFs</td><td colspan="2">Same as Ligno 90 + SP•PF, excepting lignin distribution:
6 metric tons/day to board mills, 220 metric tons/ day to PF resins, 124 metric tons/day to carbon fibers</td></tr>
</table>

[1] The demo plant extracts 9 b.d. metric tons/day of lignin from 50 b.d. metric tons/day of hardwood.
[2] There is a capacity ramp up of the full-scale plant from Year 10-12 resulting in 220, 270, and 350 b.d. metric tons/day of lignin extracted.

I. Summary of lignin-based biorefinery strategies and phased implementation (PF = phenol-formaldehyde; PU = polyurethane; CF = carbon fiber).

Feed Material	Assumed Unit Cost ($/metric ton)		Basis for Assumed Cost
	Nominal	Maximum	
Phenol	1 005	1 905	Correlation identified with the price of crude oil.
Sulfuric acid	180	240	Pricing based on historical trends dictated by phosphate fertilizers and copper industries.
Carbon dioxide	300	390	Case-specific values.
Oxygen	50	65	
Caustic	430	810	Correlation identified with the price of crude oil.
Enzymes	2 270	2 500	Latest available price in literature. A 5% increase was considered for the maximum, as prices are expected to considerably decrease with more economical technologies.
Yeast	1 875	2 060	
Biomass	100 (dry)	127 (dry)	30% of the delivery costs were attributed to transportation, which was assumed to be varying with crude oil.
Formaldehyde	210	400	Formaldehyde is produced on-site. Methanol represents around 80% of production costs, and its price is correlated to both crude oil and natural gas.
Electricity	7.9 ¢/kWh	14.8 ¢/kWh	Values adjusted to mill location based on historical trends.
Natural gas	4.35 $/GJ	7.15 $/GJ	

II. Assumed unit costs for feed materials to process.

Product	Assumed Market Price ($/metric ton)		Basis for Assumed Price
	Nominal	Minimum	
Phenol	1 005	690	Correlation identified with the price of crude oil.
Polyols	2 970	2 035	Correlation identified with the price of propylene, which is conjointly influenced by prices of crude oil and natural gas.
PAN	2 480	1 700	Based on target carbon fiber prices between 5-7 $/lb. Minimum value based on variations of acrylonitrile, therefore of propylene.
PF resin	2 000	1 485	Average price among different providers. Minimum value linked to variations of phenol and formaldehyde.
Sugar syrup	170	155	Molasses price in cattle industry-intensive U.S. states.
Isobutanol	3.08 $/gal	2.11 $/gal	Correlation identified with the price of propylene.

III. Assumed market prices for lignin-based biorefinery products

Definition of a minimal and necessary set of decision criteria

For the purposes of the case study, a database of MCDM panel criteria from many previous panels was considered. There were two criteria triage steps, (1) considering the pertinence of individual criteria, and (2) considering the family of criteria as a whole. In the first step, criteria judged not relevant, important, representative, or discriminative were screened [38]. The panel members judged the reliability of criteria based on information and assumptions used to calculate criteria metrics. The set of criteria resulting from the first step was then enhanced, by assessing that it formed a consistent family of criteria [34]. Certain criteria were combined into a single one to make a set of workable criteria for the panel, with a maximum of eight.

A set of six criteria were identified in close collaboration with panel members, a majority being related to market risk and competitiveness. **Table IV** summarizes the criteria and their interpretations as established by the panel members.

Decision-making for the "preferred" lignin-based biorefinery strategy

An MCDM panel method was employed for decision-making. Preferences regarding relative criteria importance (weights) were obtained through a pair-wise tradeoff process between criteria with the one considered most important by panel members. Biorefinery strategies could then be compared based on their overall scores, which were calculated using a weighted sum as defined by Eq. (1):

$$\text{Score}_{\text{candidate } j} = \sum_{i=1}^{N} W_i \times U_i(x_j) \quad (1)$$

where N is the number of criteria, W_i is the weight of criterion i, U_i is the utility function associated with criterion i, and x_j is the value obtained by evaluating biorefinery candidate j under criterion i. The utility function serves the purpose of bringing criteria with different units to a common basis. In this case, a linear normalization was employed, using lower and upper bounds determined by panel members based on the results of criteria evaluation.

The panel was composed of seven members, including four representatives of the forest products company, and three external members. External members are usually facultative but were included in this case at the request of the company. Quintero-Bermudez demonstrated that consistent decisions – different criteria weights but similar alternatives scores and ranking – are generally achieved even with different panel compositions [39]; however, in order for the decision to adequately reflect the company's vision, its representatives must be people with authority on project approval, which in this case was an accountant and three managers.

RESULTS

Techno-economic estimates

The techno-economic analysis results are summarized in **Table V**. The "company contribution" considers the joint venture approach used for the solvent pulping (SP) strategy.

Although these techno-economic results are mill-specific, there is an order-of-magnitude difference between costs and revenues associated with integrated (Group 1) and larger-scale (Group 2) strategies. The Group 1 strategies require relatively low capital and operating expenses, but also generate lower annual revenues compared to larger scale strategies. On the other hand, strategies in Group 2 rely on the availability of subsidies and economies-of-scale for attractive returns. Although they generate higher annual margins, the associated NPV's are lower than those of Group 1 strategies with similar lignin derivative products. Higher profitability could be expected if higher value derivatives from cellulosic sugars were to be considered; however, it was not the focus of this case study. The profitability of the Resin 90 strategy is impressive, but implies more economic uncertainties compared to other strategies.

Assessment of decision criteria

Decision-making for corporate transformation to a new product portfolio, such as the case for the lignin-based biorefinery, should not rely on profitability metrics alone. Technology and market risks are critical for this long-term diversification decision, and thus a more complete set of decision-making metrics was considered in the present study. The values for the 6 decision-making criteria identified and defined in Table IV are presented in **Table VI**. (Note: Considering a sustainability perspective, environmental, and other criteria would typically also be considered in an MCDM panel; however, the focus of the current work was on technology and market risks in addition to profitability.)

The two economic criteria (IRR and CFCE) display a similar trend, and strategies involving integrated processes are more profitable than those involving larger scale processes. Group 2 strategies have a greater impact on revenue diversification and are less vulnerable to fluctuations in energy and chemical costs. RPMC displays a unique profile that makes a direct comparison between strategies of the two groups less obvious. Considering the global picture, no candidate strategy results in criteria evaluation that are higher than all other candidates for the criteria considered. This justifies the need to allocate weights to criteria using an MCDM panel, alongside other benefits of MCDM panels, such as alignment of stakeholders.

MCDM panel outcome

IRR was selected by the panel as the most important criterion in the context of the case study, considering the importance of profitability for ensuring competitiveness of the overall site over the long term. Panel members set the target value of IRR at 25%, and an ambitious value of 75% for the upper limit of

Category	Criterion	Interpretation	Metric
Economic Risk	Internal Rate of Return (IRR)	Measure of **project profitability under normal market conditions**, considering all phases of the biorefinery strategy. The hurdle rate was set at 20%, considering the risk level expected in Year 5 of the project.	Discount rate at which NPV equals zero. $NPV = \sum_{t=0}^{25} \frac{\text{Cash flow}_t}{(1+IRR)^t} = 0$
	Cash Flow on Capital Employed (CFCE)	Ability to generate cash flows from the capital investment over the life of the project, and thereby **to improve the value of the company by lowering its debt**.	• Discount rate for future EBITs: 20% • Discount rate for capital investments: 6% $CFCE = \frac{\sum \text{present value of future EBITs}}{\sum \text{present value of capital investments}}$
Market Risk and Competitiveness	Revenue Diversification (RD)	Potential to meet revenue growth targets from new bioproducts, over the revenue from the mill in its current situation. It indicates an ability to mitigate market risk by being **less dependent on pulp sales**, due to a more **diversified source of revenues**.	$RD = \text{Importance of new revenues} \times \text{Importance of new products}$
	Competitiveness on Production Costs (CPC)	**Robustness** of the biorefinery strategy relative to an **aggressive price-cutting strategy from the competition**, based on assumptions of a low-end production price for the competition.	$CPC = \frac{(\text{Total portfolio revenue})_{\text{minimum market prices}} - \text{Operating costs}}{(\text{Total portfolio revenue})_{\text{minimum market prices}}}$
	Resistance to Energy and Chemicals Market Uncertainty (RECMU)	Vulnerability of the strategy to **production cost volatility due to the volatility of feed material costs** (product transportation and logistics not included).	$RECMU = 1 - \frac{\text{Costs of }(\text{energy} + \text{chemicals})}{\text{Total variable costs}}$
	Robustness to Poor Market Conditions (RPMC)	Ability to **afford process operation under poor market conditions** for a 6-month period, expressed by EBITDA as a percentage of the capital investment.	$RPMC = \frac{(\text{monthly EBITDA under poor market conditions}) \times 6}{\text{Total capital costs}}$

IV. Summary of decision criteria used for decision-making panel (NPV = net present value; EBIT = earnings before interest and tax; EBITDA = earnings before interest, taxes, depreciation and amortization).

the normalization range. The latter was justified by the need to encompass uncertainty of parameters that influence IRR, given especially uncertainty of data for Year 5 and beyond of the project timeline. Criteria weights and ranking that resulted from tradeoff activities are summarized in **Fig. 3**, and the overall scores obtained when combining the weights with normalized calculated outcomes for each strategy criteria are presented in **Fig. 4**.

After IRR, Competitiveness on Production Costs (CPC) was attributed the second highest weighting among the criteria, mainly due to the impact that pricing strategy has on the potential to penetrate and capture early market share. The relatively high weight of the Revenue Diversification (RD) criterion was linked with the objective of diversifying sources of revenues as part of the long-term vision of the forest product company. Cash Flow on Capital Employed (CFCE) and Resistance to Energy and Chemicals Market Uncertainty (RECMU) criteria received similar weights as indicators of profitability and robustness. Since all biorefinery strategies had positive margins under poor market conditions, panel members decided not to attribute Robustness to Poor Market Conditions (RPMC) a significant weight.

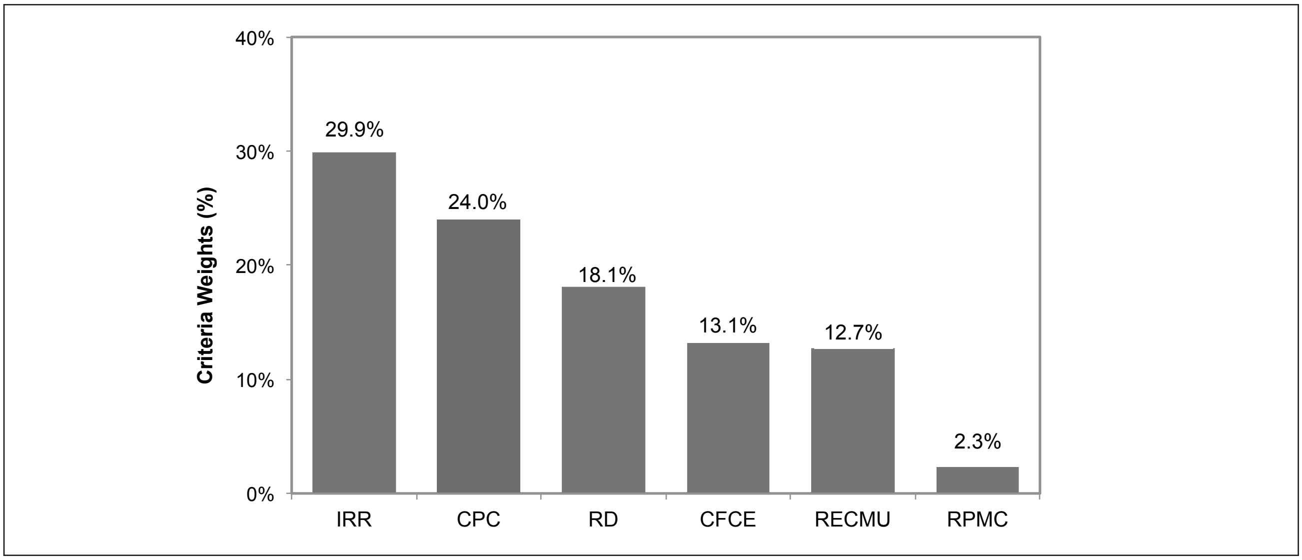
As per Fig. 4, the application of criteria weights to the different biorefinery strategies did not lead to scores disparate enough that they were easily distinguished. Criteria weights influenced strategies scores in diverse ways. Strategies involving integrated processes were preferred due their performance on economic indicators, while strategies involving larger-scale processes were preferred due to their diversification potential and robustness. The strategy Ligno 90•PF PU, ranked first, adequately combines economic and strategic advantages, being the best performer for IRR, CFCE, and CPC. Overall, strategies involving PU foams were more preferred than strategies using similar processes but promoting carbon fiber. The strategy Resin 90 also had an interesting position, with a profile distinct to other strategies of comparable scores.

		Group 1 Improve mill competitive position				Group 2 Larger-scale revenue diversification		
Indicator		Ligno 90•PF	Ligno 90•PF PU	Ligno 90•PF CFs	Resin 90	Ligno 90 + SP•PF	Ligno 90 + SP•PF PU	Ligno 90 + SP•PF CFs
Lignin production capacity		90 metric tons/day	90 metric tons/day	90 metric tons/day	90 metric tons/day 435 metric tons/day resin	350 metric tons/day	350 metric tons/day	350 metric tons/day
Capital Investment	Total project cost	32 M$	33 M$	39 M$	146 M$	432 M$	438 M$	436 M$
	Company contribution					153 M$	156 M$	154 M$
Annual Operating Costs (Phase II)	Total costs	6 M$/year	7 M$/year	7 M$/year	104 M$/year	123 M$/year	127 M$/year	126 M$/year
	Company contribution					60 M$/year	62 M$/year	61 M$/year
Annual Revenues (Phase II)	Total revenues	21 M$/year	41 M$/year	36 M$/year	287 M$/year	222 M$/year	305 M$/year	284 M$/year
	Company share					120 M$/year	162 M$/year	151 M$/year
Annual EBITDA (Phase II)		15 M$/year	34 M$/year	29 M$/year	183 M$/year	60 M$/year	100 M$/year	90 M$/year
NPV (Phases I and II combined)		17 M$	70 M$	49 M$	164 M$	6 M$	50 M$	37 M$

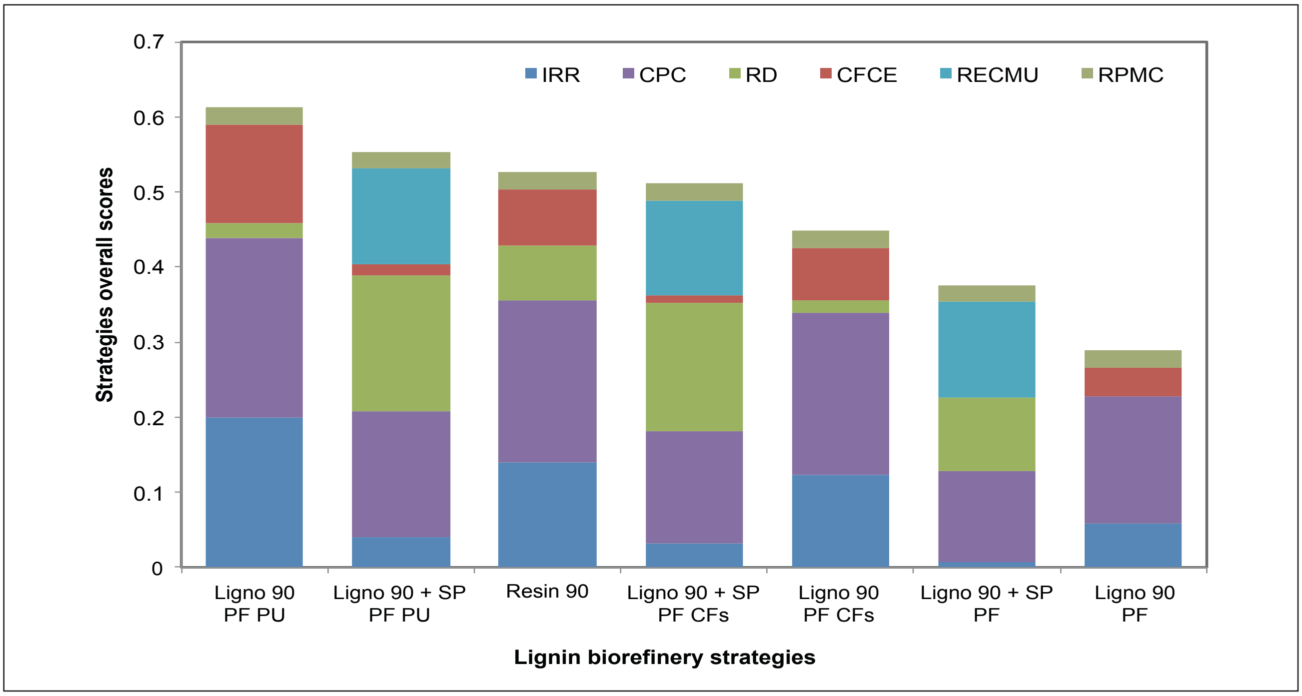
V. Summary of techno-economic results.

	Group 1 Improve mill competitive position				Group 2 Larger-scale revenue diversification		
Criterion	Ligno 90•PF	Ligno 90•PF PU	Ligno 90•PF CFs	Resin 90	Ligno 90 + SP•PF	Ligno 90 + SP•PF PU	Ligno 90 + SP•PF CFs
Internal Rate of Return (IRR)	31%	57%	43%	46%	21%	28%	26%
Cash Flow on Capital Employed (CFCE)	2.0	4.5	2.9	3.0	1.0	1.4	1.3
Revenue Diversification (RD)	2%	7%	7%	22%	29%	51%	48%
Competitiveness on Production Costs (CPC)	46%	65%	59%	58%	33%	45%	41%
Resistance to Energy and Chemicals Market Uncertainty (RECMU)	21%	30%	28%	14%	82%	83%	83%
Robustness to Poor Market Conditions (RPMC)	7%	22%	13%	4%	4%	11%	8%

VI. Summary of results of criteria evaluation.



3. Criteria weights resulting from the Multi-Criteria Decision-Making (MCDM) tradeoff panel.



4. Scores for lignin-based biorefinery strategies resulting from the MCDM panel.

Based on these results, the panel identified the top three strategies as "most preferred" for implementing the lignin-based biorefinery. The following two could eventually be reconsidered if market conditions become more favorable for their implementation. The last two candidate strategies were rejected.

DISCUSSION

A marginally profitable strategy is unlikely to be preferred. On the other hand, the IRR criterion weight is surprisingly low compared to others, due in large part to the upper bound of normalization set at 75% by the panel, as in high profitability expectations from a lignin-based biorefinery strategy by panel members.

CPC has an important impact for distinguishing between strategies and is the most important contributor for five of seven strategies. Product pricing, which is dependent on both process economics and the comparability of lignin-derived with existing products, is a determining factor for the endorsement of the lignin-based biorefinery by forestry companies.

From the perspective of distinguishing between strategies, RPMC did not play a distinctive role, as all strategies had good performance. For the assumptions of the study, the lignin-produced products from the mill have good potential to be cost-competitive compared to similar derivative products that use fossil-based feedstocks.

It is clear that the larger volume strategies are preferred due to their more significant revenue growth and their diversified product portfolio for mitigating price volatility. Combining the best two candidates, a forest product company could: (1) increase its lignin precipitation capacity and diversify the targeted lignin applications including higher value derivatives in the midterm, prior to (2) implementing a larger scale process, such as solvent pulping leading to a diversified product portfolio to simultaneously improve its market position and its robustness.

Emphasizing vertical integration by entering into the resin-manufacturing segment was also a preferred lignin-based biorefinery strategy. The score of the Resin 90 strategy shows that it can potentially create unique competitive advantage for the forestry company. Because it can partially absorb unsold volumes of lignin or eventually lignin-based resin by using it in its own board mills, such a company has the opportunity to demonstrate the application, optimize the application, and clearly identify the value proposal for lignin-based phenolic resins.

Finally, the ranking and score of the Ligno 90•PF strategy demonstrates that minimal risk strategies are unlikely to lead to a sustainable competitive position. Market demand is expected to increase as the usage of lignin derivatives for diverse applications gets mature, and a strategy relying solely on increasing the production capacity would be insufficient from a competitive point of view.

CONCLUSIONS

Recent progress towards the emergence of the lignin-based biorefinery motivated this study, which aims at the identification of promising strategies considering particularly the context of a retrofit implementation of the lignin-based biorefinery within a forest products company. This has been achieved through a case study considering seven candidate strategies for implementation at an existing kraft pulp mill where a 30 metric tons/day lignin precipitation unit is already in place. Company-specific drivers and barriers led to retaining PF resins, PU foams, and carbon fiber applications as potential market segments for lignin positioning.

The assessment of candidate strategies was made using a set of economic and market criteria. Results showed that strategies involving integrated (lignin precipitation) processes were more profitable than those involving larger scale (solvent pulping) processes, while the latter was more attractive in terms of revenue diversification and were more robust to price volatility on energy and chemical markets.

Criteria weighting was made using a Multi-Criteria Decision-Making (MCDM) panel, during which Internal Rate of Return (IRR) received the highest weight. Nevertheless, the criterion representing price competitiveness was the highest contributor to strategy scores. Price competitiveness relative to competing fossil-based products is expected to be critical to the development of lignin biorefinery, both for market penetration and positioning. The MCDM panel members identified that the top three lignin-based biorefinery strategies should be retained as “preferred”. The first-ranked strategy would sell lignin for PF resins and PU foams at a low volume and resulted in strong economic returns, cash flow generation and cost competitiveness. The second-ranked strategy considered the same applications for lignin but at a larger scale, and the third-ranked strategy considered on-site manufacturing of a lignin-based PF resin. **TJ**

ACKNOWLEDGMENTS

This study was funded by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors would like to thank the industrial partners in the project that provided data and contributed to validating assessment results, as well as panelists who participated in MCDM sessions.

LITERATURE CITED

1. Ragauskas, A., “Lignin Overview,” Institute of Paper Science and Technology, Atlanta, GA, USA. Available [Online] http://www.ipst.gatech.edu/faculty/ragauskas_art/technical_reviews/Lignin%20Overview.pdf <18April2017>.
2. Zhang, Y.-H., *J. Ind. Microbiol. Biotechnol.* 35(5): 367(2008).
3. Macdonald, C., *Pulp Pap. Can.* 117(5): 16(2016).
4. Kouisni, L., Gagné, A., Maki, K., et al., *ACS Sustainable Chem. Eng.* 4(10): 5152(2016).
5. Öhman, F., Theliander, H., Tomani, P., et al., pat. WO 2006031175 A1 (March 23, 2006).
6. Kouisni, L. and Paleologou, M., pat. US20110297340 A1 (Dec. 8, 2011).
7. Agbor, V.B., Cicek, N., Sparling, R., et al., *Biotechnol. Adv.* 29(6): 675(2011).
8. Diffo Téguia, C., Albers, R., and Stuart, P., *TAPPI J.* 16(3): 157(2017).
9. Holladay, J.E., Bozell, J.J., White, J.F., et al., *Top Value-Added Chemicals from Biomass Volume II—Results of Screening for Potential Candidates from Biorefinery Lignin*, U.S. Department of Energy, Oak Ridge, TN, USA, 2007.
10. Smolarski, N., “High-Value Opportunities for Lignin: Unlocking its Potential,” Frost & Sullivan, San Antonio, TX, USA, 2012. Available [Online] http://www.greenmaterials.fr/wp-content/uploads/2013/01/High-value-Opportunities-for-Lignin-Unlocking-its-Potential-Market-Insights.pdf <12April2017>.
11. LigniMatch, “Future use of lignin in value added products,” Chalmers University of Technology/University of Gothenburg, Gothenburg, Sweden. Available [Online] http://www.gmv.chalmers.gu.se/digitalAssets/1448/1448662_roadmap.pdf <12April2017>.
12. Gosselink, R., “Future perspectives of organosolv lignins,” DLO-BIOCORE, Wageningen, Netherlands, 2014. Available [Online] http://www.biocore-europe.org/file/2_1%20BIOCORE%20R%20Gosselink%20DLO%20Organosolv%20lignins.pdf <18April2017>.
13. Wang, M., Leitch, M., and Xu, X., *Eur. Polym. J.* 45(12): 3380(2009).

14. Çetin, N.S. and Özmen, N., *Int. J. Adhes. Adhes.* 22(6): 477(2002).

15. Matsushita, Y., *J. Wood Sci.* 61(3): 230(2015).

16. Mahmood, N., Yuan, Z., Schmidt, J., et al., *Eur. Polym. J.* 68: 1(2015).

17. Naskar, A.K., "Developing low cost carbon fiber for automotive lightweight composites," *32nd Annu. Meet. Counc. Chem. Res.*, Council for Chemical Research, Washington, D.C., 2011.

18. Nordström, Y., Norberg, I., Sjöholm, E., et al., *J. Appl. Polym. Sci.* 129(3): 1274(2013).

19. Kadla, J.F., Kubo, S., Venditti, R.A., et al., *Carbon* 40(15): 2913(2002).

20. Norberg, I., "Carbon fibres from kraft lignin," Ph.D. thesis, KTH Royal Institute of Technology, Stockholm, 2012.

21. Chambost, V., McNutt, J., and Stuart, P.R., *Pulp Pap. Can.* 109(7): 19(2008).

22. Diffo Téguia, C., Chambost, V., Sanaei, S., et al., in *Forest Value Chain Optimization and Sustainability* (S. D'Amours, Eds), CRC Press, Boca Raton, FL, USA, 2016, Chap. 3.

23. Archer, N.P. and Ghasemzadeh, F., *Int. J. Proj. Manage.* 17(4): 207(1999).

24. Henriksen, A.D. and Traynor, A.J., *IEEE Trans. Eng. Manage.* 46(2): 158(1999).

25. Verbano, C. and Nosella, A., *Eur. J. Innovation Manage.* 13(3): 355(2010).

26. Thamhain, H.J., *Eng. Manage. J.* 6(3): 3(2014).

27. Papalexandrou, M.A., Pilavachi, P.A., and Chatzimouratidis, A.I., *Process Saf. Environ. Prot.* 86(5): 360(2008).

28. Sacramento-Rivero, J.C., *Biofuels Bioprod. Biorefin.* 6(1): 32(2012).

29. Posada, J.A., Patel, A.D., Roes, A., et al., *Bioresour. Technol.* 135: 490(2013).

30. Niekamp, S., Bharadwaj, U.R., Sadhukhan, J., et al., *J. Ind. Prod. Eng.* 32(1): 23(2015).

31. Vincke, P., *Multicriteria Decision Aid*, John Wiley and Sons, New York, 1992.

32. Keeney, R.L. and Raiffa, H., *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*, Cambridge University Press, New York, 1993.

33. Roy, B., *Méthodologie multicritère d'aide à la décision*, Economica, Paris, 1985.

34. Roy, B. and Bouyssou, D., *Aide multicritère à la décision: Méthodes et cas*, Economica, Paris, 1993.

35. Hytönen, E. and Stuart, P.R., *Pulp Pap. Can.* 110(5): T58(2009).

36. International Energy Agency, "World Energy Outlook 2015 - Chapter 1: Introduction and scope," 2015. Available [Online] http://www.worldenergyoutlook.org/media/weowebsite/2015/WEO2015_Chapter01.pdf <18April2017>.

37. U.S. Energy Information Administration, "Annual Energy Outlook 2015 with Projections to 2040," 2015. Available [Online] https://www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf <18April2017>.

38. Bouyssou, D., in *Readings in Mutiple Criteria Decision Aid* (C.A. Bana e Costa, Ed.), Springer Verlag, Berlin, Germany, 1990, pp. 58-80.

39. Quintero-Bermudez, M.A., Janssen, M., Cohen, J., et al., *TAPPI J.* 11(11): 9(2012).

ABOUT THE AUTHORS

Téguia

Stuart

D'Amours

Albers

We chose to study this topic because the decision about long-term lignin-based biorefinery strategies that meet company needs and values is not obvious. We have previously conducted research on Multi-Criteria Decision-Making (MCDM) methodology, including several papers published in *TAPPI Journal*.

The most difficult aspect of this research was assembling an interested industry panel willing to invest their time in becoming familiar with the MCDM methodology. We did enhance our ability to conduct effective MCDM panels through this exercise. Our most interesting finding was that companies are more concerned about downside risk than they are about making money!

Through this research, mills can better appreciate (a) long-term lignin-based biorefinery strategies, and (b) their relative strengths and weaknesses, especially regarding risk. The next step will be for our industry partner to decide on their longer-term lignin-based biorefinery strategy.

Diffo Téguia is post-doctoral student and Stuart is professor at Polytechnique Montréal, Montréal, QC, Canada. D'Amours is professor, Université Laval, Quebec City, QC, Canada. Albers is manager, Energy and Bioproduct Development, West Fraser Timber Co. Ltd., Quesnel, BC, Canada. Email Stuart at paul.stuart@polymtl.ca.