Early design-stage biorefinery process selection

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ABSTRACT: A methodology for early design-stage evaluation of biorefinery processes that uses multicriteria decision-making (MCDM) panels was developed with the goal of screening out less promising options. Panel members were asked to rate the relative importance of a set of evaluation criteria for biorefinery process implementation at a pulp and paper mill. Three different panels were conducted, each with this same objective. This report compares and assesses the results from the panels. Two of the MCDM panels were comprised of biorefinery specialists of similar backgrounds from government and academia, and the third panel consisted of pulp and paper industry decision makers. In general, consensus was high between all three panels, and especially between the two biorefinery specialist panels; however, certain differences were noted with the industry panel. For three out of eight criteria, these differences were attributable to a difference in the perspective of the forest industry decision makers and biorefinery specialists. For example, for the return on investment criteria, the specialist panels gave a significantly higher importance to current information from technology suppliers because it provides an important short-term perspective. In contrast, the forest industry decision makers thought that information about a particular technology should be critiqued and adjusted based on a systematic assessment of likely future process performance. Differences between the other criteria were attributed to differing interpretations of the criteria.

Application: This study gives a detailed overview on how to systematically eliminate process-product biorefinery strategies during early stage design by considering approximate process data and other information assessed in a consistent manner using simple criteria, for which weights can be identified clearly through a panel of decision makers having diverse perspectives.

The North American forest sector has faced significant economic challenges in recent decades [1]. Once having a position of global leadership in forest products manufacturing, the industry is now seeking opportunities to survive, and make a continued contribution to society through responsible exploitation of the renewable forest resource. At the same time, there have been significant reductions in capital investment in the forestry sector, and a reduced capacity for innovation and product development [2]. Individual pulp and paper mills can either continue their emphasis on reducing operating costs and improving their cash flow, or couple this with an objective to renew their business strategies and benefit from emerging opportunities that can potentially improve their profitability over the longer term [3]. The biorefinery concept has thus increasingly become an alternative for transformation of the forestry industry, potentially leading to the production of biofuels and added-value biomaterials and biochemicals [4].

The most appropriate implementation configuration(s) of the biorefinery remains far from obvious for most forestry companies. What is clear is that the biorefinery implementation strategy will mostly differ from one forestry company to another, which makes it essential to have an evaluation methodology of biorefinery technology options and the implicated products that allows for the particular values and situation of companies to be systematically expressed. The Forest Products Association of Canada (FPAC) notes that, "bio-energy and bio-product opportunities are stronger economically and socially when integrated within the traditional industry's operations rather than on a standalone basis. Both the traditional and emerging bio-energy and bio-products operations enjoy higher economic returns and perform better when integrated. The forest products industry produces far more jobs and generates greater GDP than emerging bio-industries in isolation" [5]. Forestry companies need to execute a systematic process that helps to identify their unique biorefinery strategies that will provide long-term competitive advantages by integrating new product families into their existing portfolio [6], and should avoid strategies that provide short-term but unsustainable returns. This imperative is being increasingly recognized by forestry companies.

EARLY-STAGE BIOREFINERY DECISION-MAKING

Identifying a biorefinery strategy implies a complicated decision-making process that must take into account multiple and interdisciplinary considerations; it should not be based solely on a return on investment (ROI) evaluation. For instance, forest biorefinery (FBR) strategies potentially can (a) help forestry companies to optimize the harvesting and use of forest biomass, (b) enlarge product portfolios with bioproducts to improve company profit margins, (c) optimize mill energy consumption, and (d) reduce their GHG emissions and land use impact [7]. For example, systematic analyses must consider a range of methodologies related to economic and technological feasibility, technology risks for emerging technologies, market opportunities and risks, partnership potential, value at the supply chain management level, energy consumption, and environmental footprints.

At the early biorefinery design stage, the scarcity and uncertainty of information about emerging biorefinery technologies currently under development represent a significant risk regarding scale-up, overall performance (e.g., yields, production capacities, operating costs, etc.), and future improvements in capital and operating cost performance for a technology as it matures. These risks directly affect ROI calculations and influence the confidence level of calculated values. Using another example, most emerging FBR technologies have not reached the demonstration scale yet, and many have focused on ethanol production, a commodity product requiring large quantities of biomass for an appropriate production scale [8]. This implies risk associated with process scale-up and feedstock supply that also should be taken into account when evaluating the implementation of FBR technologies at the early design stage [9]. However, forestry companies typically have limited access to validated information and the resources needed to evaluate the numerous emerging technologies and product markets in adequate detail, which limits their capacity to make well-informed decisions that are critical to their longer-term sustainability.

The comparison of biorefinery product-process options is far from obvious, given the multitude of pathways [10], the recent development of FBR technologies and their maturity level (i.e., bench, pilot, and demonstration scale), and the various retrofit installation possibilities, which in turn depend on the infrastructure at pulp and paper mills, and specific company interests and values [11]. This paper presents a methodology that forest companies can apply to identify promising FBR technologies and products from the multitude of possibilities, based on limited information, in a practical manner.

Previous studies comparing the economic performance of bioproducts manufacturing technologies have used a high decision-making level, and have not focused on the investing company perspective [12,13]. Foust [14] compared two biochemical and thermochemical pathways for producing biofuels based on capital and operating costs, energy efficiency, and emissions to the environment. This study proposed that some technical (i.e., catalyst inhibitors and poisons, feedstock sources, integration, and recycle possibilities) and market (i.e., product diversification) considerations also should be taken into account for a more rigorous comparison. Thorp [15] and FPAC [5] developed a framework for identifying promising FBR technologies at the early design stage using a specific set of criteria, while considering that the users of this framework do not have access to basic economic metrics such as ROI. Thorp [15] suggests identifying opportunities based on raw materials supply, market opportunities, most promising pathway, and most promising technology within a pathway. FPAC [5], in contrast, is evaluating six lines of inquiry for many biorefinery technologies including 1) market readiness of the emerging technologies; 2) key economic, social, and environmental metrics related to the main existing and emerging bioproducts; 3) economic fiber supply; 4) market potential of emerging bioproducts; 5) new approaches to managing the value chain; and 6) development of partnerships. Pätäri [16] used a Delphi methodology (a panel-based method collecting opinions from specialists with a background in different industries) to identify industry-level and company-level factors that are most likely to influence the bioenergy sector and its value creation potential. This panel-based approach "proved to be a valuable research tool with which it was possible to obtain comprehensive information on a subject that lacks historical and financial data, and yet requires input from many quarters" [16].

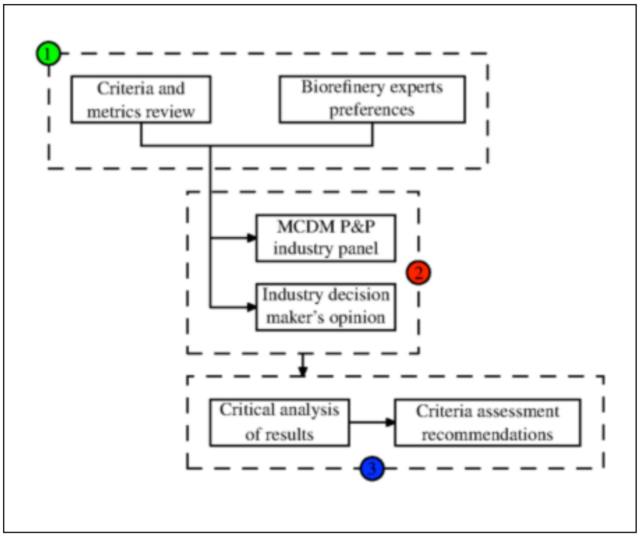
In earlier work directly related to this study, Cohen et al. [9] defined a set of multidisciplinary criteria for assessing emerging FBR technologies at the early design stage. The definition of these criteria was based on a literature review and several internal revisions. In carrying out a multicriteria decision-making (MCDM) panel, FBR specialists were asked to elicit the importance of different criteria when implementing biorefinery technologies at a specific mill. The relative weight assigned by panel members to each criterion was then used to identify the competitive advantages of different FBR technologies. This approach permitted less promising technologies to be screened out, based on a set of well-defined criteria addressing critical issues to be considered for early stage FBR design decision-making. However, the results of an MCDM panel are likely a function of the background of each of the panel members, and of the panel dynamics resulting from panel members' personalities and values. MCDM criteria must be clearly defined to allow a common interpretation among the panel members. An interesting question arose concerning the reproducibility of the MCDM method: Do subjectivity in criteria interpretation or changes in panel dynamics influence the MCDM panel results to a large extent, or do different panels arrive at similar conclusions after the panel process? The methodology described in this paper was developed to address this important question and refine the MCDM panel approach.

OBJECTIVES

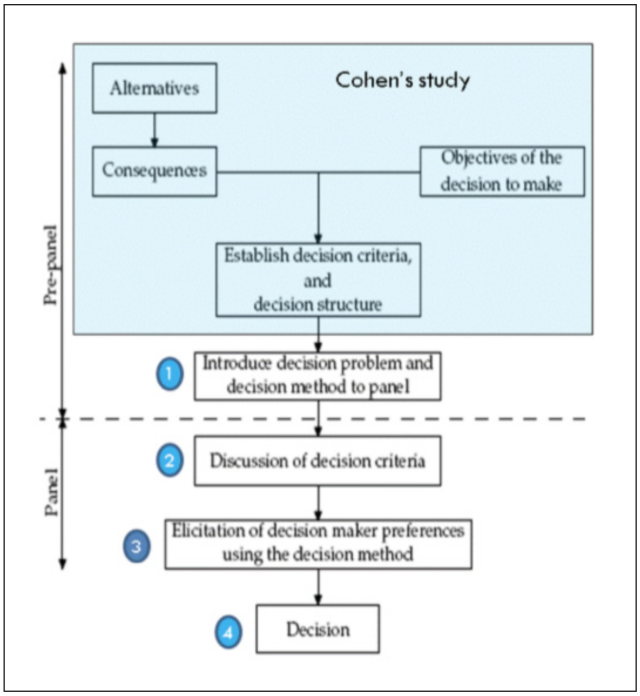
The objectives of this analysis were to evaluate the differences between the results of two different MCDM panels involving FBR (technology) specialists having similar backgrounds, and to compare and contrast these results with those from a panel that consisted of forest industry decision makers from mill and corporate levels.

METHODOLOGY

A three-step overall methodology for the panels (**Fig. 1**) was used to address the objectives of this study. In the first step, a set of process-product biorefinery strategies were identified, and the metrics for these were calculated according to meth-



1. Methodology for criteria assessment.



2. Multicriteria decision-making (MCDM) panel roll-out methodology.

ods described by Cohen et al. [9]. The criteria and related metrics were evaluated by two different panels comprised of biorefinery specialists. During the second step, the same criteria were evaluated by forestry company decision makers. The objective of this step was to identify differences and similarities between FBR specialist and industry perspectives, and the possible causes for these differences. The third step of the methodology for the criteria assessment consisted of a statistical analysis of the results obtained during the three panels. It identified the differences between the results of the FBR specialist panels (B1, B2), and compared and contrasted those with the industry panel (PP), taking into account the consensus between panel members.

The roll-out for the two biorefinery specialist panels (B1 and B2) and the pulp and paper industry panel (PP) was inspired by previous work [9,17], and consisted of four steps (**Fig. 2**):

1. Presentation of the decision problem, definition of the metrics and criteria, and calculated results for each product-process biorefinery strategy.
2. Interpretation of the MCDM criteria by each panel member until an interpretation consensus is achieved.
3. Elicitation of panel members' preferences.
4. Calculation of the decision weights [17].

Consensus indicates the level of agreement between the panel members after a clear definition and interpretation of the evaluation criteria have been established. A measure of consensus was defined as the normalized standard deviation of the panel members' trade-off values for each criterion and a consensus evaluation scale was proposed (**Table I**). The values in Table I were established from an analysis of the results. The ranges were set to qualitatively, but clearly, distinguish relative consensus. Statistically, the MCDM panels were considered as independent samples, and a normal distribution for the criteria weights was assumed for the analysis approach.

Level of Consensus	Normalized Score
High agreement (H)	$0 \le c \le 0.4$
Good agreement (G)	$0.4 < c \le 0.7$
Relatively less agreement (RL)	$0.7 < c \le 1$

I. Consensus (c) evaluation scale.

A pair-wise t-test comparison [17] was carried out to evaluate whether the FBR panels' results differed significantly from the industry panel.

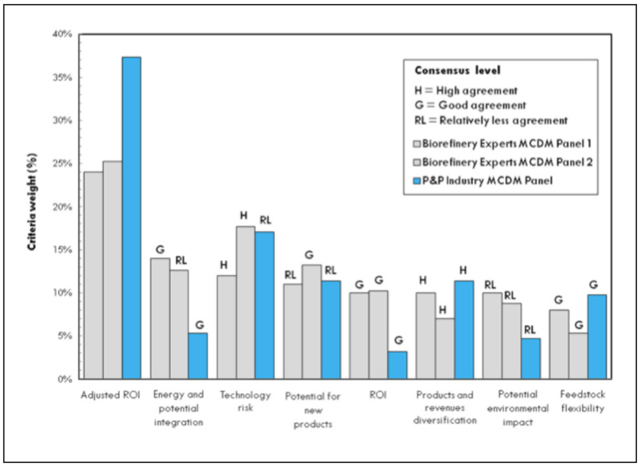
$$Normalized\_score = \frac{\sigma_{x_{ij}}}{\sigma_{\max}}$$

where:
σ = Standard deviation
χ = Trade-off values
i = Criterion number
j = Panelist number

RESULTS AND DISCUSSION

Criteria and weighting interpretation

Figure 3 summarizes the overall results from the three panels. The criterion termed "adjusted ROI," which takes into account estimated future technology improvements for the ROI calculation, was chosen as the most important criterion by all three panels (Fig. 3). This unexpected result indicated that expert and industry panel members felt that an interpretation of the information supplied by biorefinery technology suppli-



3. Weights and consensus comparison between three MCDM panels.

No.	Criterion	Significant difference between the two biorefinery specialist panels?
1	Return on investment (ROI)	No
2	Adjusted ROI	No
3	Feedstock flexibility	No
4	Technology risk	Yes
5	Energy and potential integration value	No
6	Product and revenue diversification	Yes
7	Potential for new products	No
8	Potential environmental impact	No

II. Results of the comparison between the two biorefinery specialists MCDM panels (t-test, p=0.05).

ers is critical for their evaluation, and that the future capital and operating cost performance of a biorefinery technology might be similar to or very different from the technology supplier claims. This opinion was more pronounced for the industry panel than for the expert panels. Because of this high weighting for adjusted ROI, the directly calculated ROI had a lower weighting than anticipated. Figure 3 also shows the level of consensus reached during each panel (high agreement, good agreement, and relatively less agreement). The consensus measure was not calculated for the panel members' agreement regarding the adjusted ROI criterion because of the trade-off method used for the calculation of the weighting criteria, for which panel consensus must be unanimous for the most important criterion.

Tables II and **III** summarize differences between the two biorefinery specialist panels, and between each of the biorefinery specialist panels and the industry panel. A statistical difference was found between the biorefinery specialist panels for only two criteria, whereas greater differences were found between the specialist panels and the industry panel. The biorefinery specialist panels agreed that, given the economic imperative of forestry companies, the ROI criterion provided an important short-term perspective for technology evaluation. They had a greater emphasis on having good revenues now, without considering future technology generations and the uncertainty of technology supplier information. Nevertheless, the specialist panel members recognized that data provided by biorefinery technology suppliers is less certain, especially because of different levels of optimism between different technology suppliers. Similar opinions of the specialist panels resulted in statistically equal weights for this criterion. On the other hand, forest industry decision makers were more skeptical about the information provided by technology suppliers, and they agreed that revising such informa-

No.	Criterion	Significant difference between biorefinery specialist 1 panel and industrial panel?	Significant difference between biorefinery specialist 2 panel and industrial panel?
1	Return on investment (ROI)	Yes	Yes
2	Adjusted ROI	Yes	Yes
3	Feedstock flexibility	No	Yes
4	Technology risk	Yes	No
5	Energy and potential integration value	Yes	Yes
6	Product and revenue diversification	No	Yes
7	Potential for new products	No	No
8	Potential environmental impact	No	No

III. Results of pair-wise comparisons between the two forest biorefinery specialists MCDM panels and the industrial panel (t-tests, p=0.05).

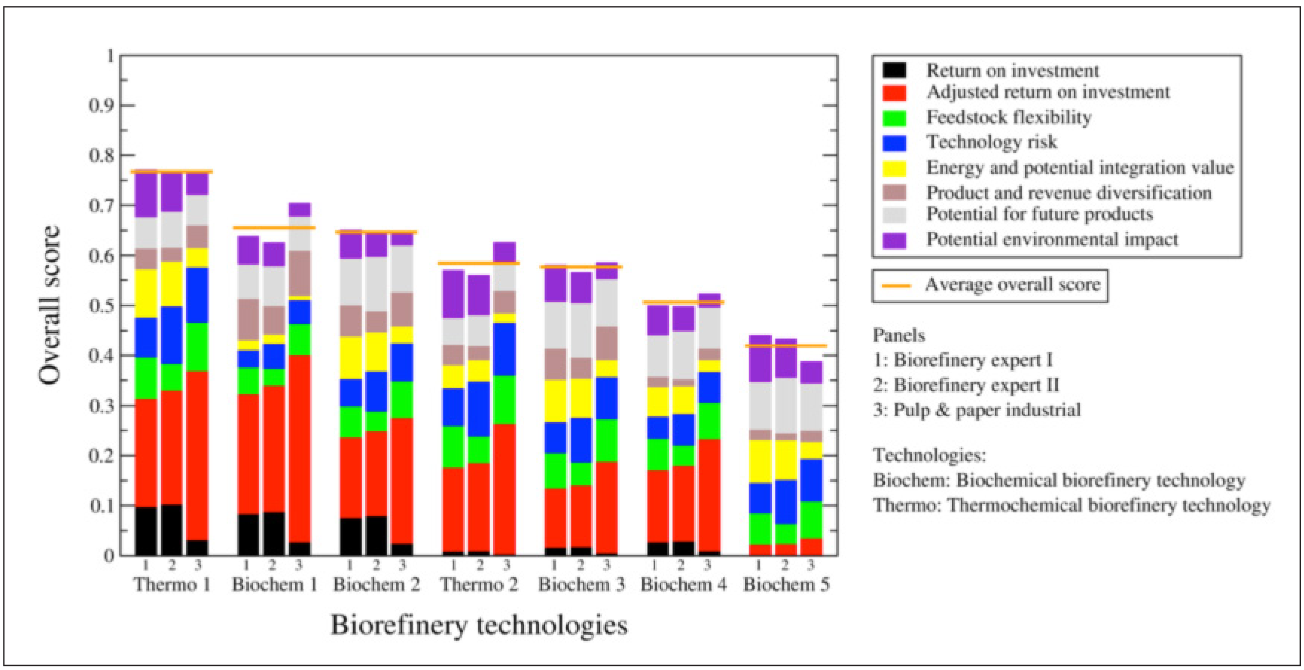
tion would give them more confidence when making a decision concerning biorefinery strategy. Furthermore, the industrial panel members agreed that the adjusted ROI criterion provided more comparable values between options. This result indicates that industry decision makers do not want to rely on information provided by technology suppliers without doing a critical analysis of this information. It also might reflect the risk-averse decision behavior of the industry decision makers, which is in accordance with the finding of Janssen and Stuart [17] that, according to another panel, the forest industry's risk-averse investment culture is the main barrier for implementation of biorefinery technology.

Regarding the feedstock flexibility criterion, the three panels agreed that this criterion was very important, but it was not especially relevant when calculated for the particular case study, and thus the criterion had the lowest weight. Nevertheless, a qualitative difference was identified between the second biorefinery specialist panel and the two others. The panel members of B1 and PP considered that the possibility to process diverse sources of biomass would be a commercial and operating advantage for biorefinery technologies, whereas panel B2 members felt that feedstock availability (economically viable at large quantities) is more important than feedstock flexibility and thus gave a lower weight.

The importance of the technology risk criterion was consistent – it was the third most important criterion in the first biorefinery specialist panel and second in the two other panels. Although the industry panel had relatively less agreement for this criterion (Fig. 1), this resulted mainly because one of the panel members considered this criterion to be less important because a high-risk technology could represent a competitive opportunity for forestry companies over those using less risky technology options.

The perspectives of biorefinery specialists and industry decision makers regarding the energy and potential for integration criterion differed significantly (Table III). Panels B1 and B2 gave weights of 14% and 13%, respectively, to this criterion, but panel PP only gave it a 5% weight. The biorefinery specialists considered the potential for integration of FBR technologies to be a key component to enhance the core business of pulp and paper mills to keep operating the mill while taking advantage of the commercial and environmental benefits offered by the developing biorefinery. On the other hand, during the industry panel, the potential for integration was considered more as a bonus. According to industrial panel members, the mill and the biorefinery each would need to be able to provide attractive profit margins.

The two market-oriented criteria ("product and revenue diversification" and "potential for new products") received similar weights in all three panels. The panelists agreed that it is important to diversify revenue streams by looking for economic benefits from co-product commercialization, and developing and commercializing new products in the future. Nevertheless, there were some differences in consensus regarding the importance of these criteria between the panels. Co-products commercialization ("product and revenue diversification") had a high level of consensus for each panel, whereas the importance of potential for new products had relatively less agreement in panels B1 and PP and a good consensus level in panel B2. The lower agreement in panel B1 was because one panel member believed it was not important to consider future new products at this early stage of decision making and that it



4. Technology ranking comparison between three MCDM panels. Note: these results are specific to the case study for which the MCDM panels were conducted, and cannot be interpreted as being valid for any other mill case.

No.	Criterion	Biorefinery Specialist Perspective	Forest Company Perspective
1	Return on investment (ROI)	Shared importance with adjusted ROI criterion. Short-term perspective: looking for receiving high revenues as soon as possible without considering future technology improvements and reductions in operating costs.	Low relative importance. Higher skepticism concerning technology supplier information.
2	Adjusted ROI	Shared importance with ROI criterion.	ROI estimations based on future technology improvements are more trustworthy and allow a better basis for comparison.
3	Feedstock flexibility	Feedstock should be available near the mill in high amounts and at low cost.	Being able to process different sources of biomass represents a commercial advantage.
4	Technology risk	Considered technology risk to be indirectly reflected in adjusted ROI; however, this is not obvious.	Better understanding of criteria definition. More consistent ranking.
5	Energy and potential integration value	Key component to preserve the core business of pulp and paper mills, enhancing the mill energy efficiency.	Additional, but separate, advantage. Considering integration to keep operating a mill may not be a good option in the long term, considering the potential for an exit strategy from pulp and paper products.
6	Product and revenue diversification	Panel members attributed more importance to developing new products in the future.	Panel members considered the two market-oriented criteria to have almost equal importance.

IV. Summary of significant differences between MCDM panels.

would be enough to develop a strategy that benefits from co-products to diversify revenue sources. Regarding product and revenue diversification, panel B2 members attributed more importance to developing new products in the future than taking advantage of co-products commercialization.

BIOREFINERY TECHNOLOGY RANKING

The decision weights of each MCDM panel and the values of the criteria metrics were used to rank the same FBR technologies studied by Cohen et al. [9]. Figure 3 shows the relative preference for different process-product biorefinery strategies, when applying the panel weights. We can conclude that the MCDM methodology resulted in similar results despite differences in consensus and in criteria interpretation between the three panels.

The average overall scores for biochemical technologies 1, 2, and 3, and thermochemical technology 2 (**Fig. 4**) were quite similar, which reflects the difficulty at this early stage of decision making to make a selection between emerging FBR technologies. Even so, the objective of this tool is to screen out less promising alternatives. Based on a review of the results, the three MCDM panels each concluded that biochemical technologies 4 and 5 should not be considered for further analyses at their actual stage of development, for this particular case study.

CONCLUSIONS

The forest biorefinery offers an interesting opportunity for forestry companies to transform their business model over the short-term and longer-term, and for companies that develop a unique competitive advantage using a sustainable business strategy. MCDM is a "formalization of common sense for decision problems which are too complex for informal use of common sense" [19]. It provided the information necessary to explain differences in outcomes, and provided for effective information transfer and productive discussion between panel members having different understandings of biorefinery evaluation criteria.

To systematically eliminate process-product biorefinery strategies during early stage design it is essential that 1) approximate process data and other information are systematically assessed in a consistent manner between processes, 2) simple criteria are defined and can be clearly interpreted by a panel of decision makers, 3) a panel of decision makers is assembled having diverse perspectives, 4) an MCDM process is executed whereby decision makers express and justify their values, and 5) results are interpreted so that the reasons for different process weights can be clearly identified.

Six differences were identified between the biorefinery specialist and industry panels based on a statistical analysis (**Table IV**). For three of the criteria (ROI, adjusted ROI, and energy and potential for integration value), these differences are attributable to a difference in the perspective of the forest industry decision makers and biorefinery specialists, whereas the differences between the other criteria were an issue of a different interpretation of the criteria (Table III).

Despite differences in consensus and some significant differences in interpretation between the three panels, the average overall technology score was consistent, and resulted in the same conclusion regarding which technologies to eliminate. These results would, however, be different in each case, depending on the mill characteristics and company interests. **TJ**

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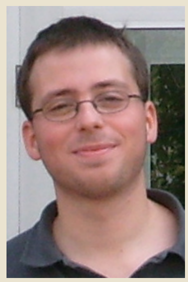

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The biorefinery sector is rapidly growing and many technology opportunities are being developed in the marketplace. As a consequence, it is important to give guidance to the pulp and paper industry, and more globally, forest industry decision makers, regarding biorefinery process and product combinations selection for their further implementation.

This work is a follow-up on work we previously did on how to create a methodology for early design-stage biorefinery process selection based on criteria definition, evaluation, and weighting published in last month's *TAPPI Journal* [11]. The interesting aspect here is the focus on the investing company perspective.

One of the most difficult aspects of this work was to ensure that the particular values and situation of all companies could be taken into account during the panels. Because the most appropriate implementation configuration(s) of the biorefinery remain far from obvious for most forestry companies, and because implementation strategies will differ from one company to another, the problem was addressed by systematically referring to the same methodology during each panel.

A surprising aspect of the study was the relatively high degree of consensus between industry decision makers and biorefinery specialists from academia and government.

This study shows an interesting and concrete application of a methodology developed to help forestry decision makers and mill managers to see how to start transforming their business model over the short-term and longer-term using biorefinery processes, and to develop a unique competitive advantage using a sustainable business strategy.

Our next step is to focus on more detailed stages of design to pursue the selection of biorefinery process and product combinations for their future implementation in forestry companies.

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