Early-stage design methodology for biorefinery capital appropriation

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ABSTRACT: This paper presents a methodology for enhancing the strategic investment decision-making process for retrofit forest biorefinery (FBR) implementation. This is achieved by improving the link between retrofit process design and capital appropriation activities through cost accounting. This methodology is based on step-wise screening of retrofit alternatives where (1) traditional techno-economic analysis and multivariate stochastic risk analysis are used in the first pre-screening step, and (2) an advanced analysis framework based on steady-state process modeling, product costing using principles of activity-based costing (ABC), and panel-based multicriteria decision-making (MCDM) is used in the second screening step. In the MCDM, financial- and risk-based decision-making criteria are used. A case study considering the retrofit implementation of a biorefinery into a kraft pulp and paper mill demonstrates the methodology.

Application: This work highlights the potential of existing process and cost-analysis capabilities to produce information for strategic investment decision-making related to retrofit forest biorefinery implementation, systematically incorporating uncertainty into the decision-making.

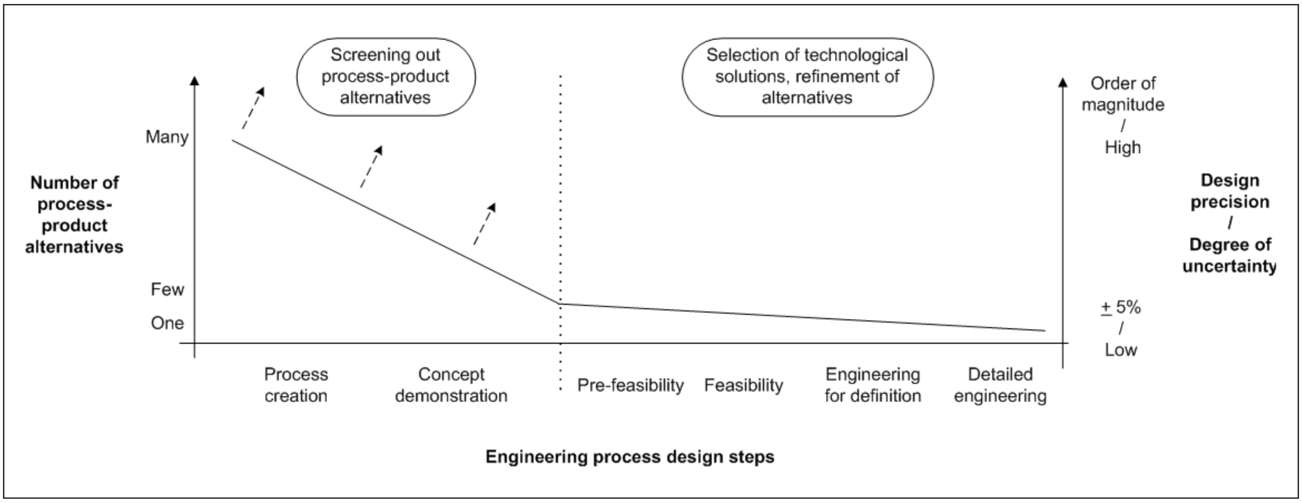
A forest biorefinery (FBR) is potentially an environmentally sustainable approach for supplying part of society's energy, chemical, and material demands. Increasingly, it is being considered as a potential future business opportunity for the traditional forest industry. The FBR targets the same markets as the traditional petrochemical industry. The current pulp and paper industry's relatively poor financial performance in traditional paper-producing countries, where demand for paper and related products is declining compared to new mills in emerging paper-producing countries, makes investment decisions regarding the FBR challenging. This low-cost competitiveness results partly from aging assets and high energy costs. Thus, pressure on the design and decision-making processes to identify the right opportunities is made complex because retrofit projects must have two goals (1) lowering pulp and paper production costs and (2) producing bioproducts profitably – in the context of changing and uncertain product demand.

Identification and management of the characteristics and uncertainties of process technologies and the new FBR business are essential for strategic investment decision-making. Currently, many methods are applied at different business lifecycle levels to determine the impacts of uncertainties. At the process level, retrofit and greenfield process design methods and process analysis tools are used to investigate feasibility and profitability of operational and strategic projects. On the other hand, at the business or facility level, advanced cost accounting methods are used to analyze manufacturing system cost-performance, financial reporting is conducted to report business performance periodically, and group decision-making is utilized in strategic planning and investment decision-making.

RETROFIT PROCESS DESIGN FOR FOREST BIOREFINERY

Various FBR process strategies and designs have been proposed. Generally, biorefinery processes are categorized into biochemical and thermochemical pathway processes. For an integrated forest biorefinery, the division into *adjacent* biorefineries and *tightly integrated* biorefineries, based on the level of integration, is more useful. Adjacent processes employ existing systems, such as the power island, but do not otherwise interfere with the pulp and papermaking process streams, whereas tightly integrated biorefinery processes exchange mass and energy with the existing pulp and paper processes. Examples of *tightly integrated* FBRs include extraction of hemicellulose prior to pulping for ethanol and biochemicals production using green liquor [1-3], hot-water [4,5], or partial dilute-acid prehydrolysis [6]; or black liquor gasification combined cycle system for Tomlinson recovery boiler replacement and simultaneous biofuels production [7,8]; or carbon dioxide and sulfuric acid utilization for lignin precipitation and filtration from black liquor [9]. *Adjacent* FBR processes include, for example, thermochemical treatment of bark or forest biomass using steam-reforming [10] or high-temperature gasification [7, 8] followed by Fischer-Tropsch liquids (FTL) or mixed alcohols synthesis, or first-generation biofuels production from corn [11,12].

Much of the literature on FBR involves prefeasibility level analyses of only one FBR technology (**Fig. 1**). Several retrofit process design methodologies have been proposed for the



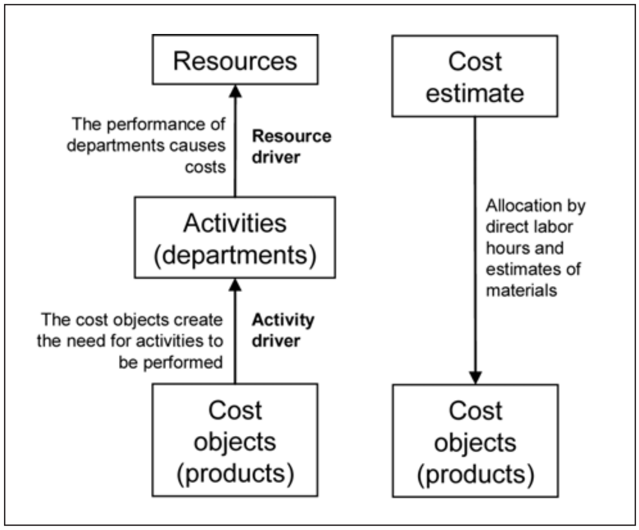
1. Engineering process design steps and their main functions.

early stage process design in general. Janssen proposed a generic retrofit process design methodology consisting of process and supply-chain level assessment steps, targeting more sustainable capital spending decisions [13]. Uerdingen, Fisher, et al. demonstrated the use of a novel methodology for systematic identification, development, and evaluation of retrofit design alternatives with and without capital investment using a case study in the fine chemicals industry [14,15], and Svensson et al. studied process integration investment decision-making under uncertainty, especially targeting energy efficiency improving strategies [16,17]. More comprehensive design methodologies specifically for FBR design are lacking. Ince, Bilek, et al. have evaluated a hypothetical gasification-based FBR business concept [18], and Bilek, Ince, et al. have analyzed a hypothetical value-prior-to-pulping thermomechanical pulping (VPP-TMP) business concept [19], including Monte-Carlo analysis to account for uncertainties in key process parameters and product prices.

COST ANALYSIS IN INVESTMENT DECISION-MAKING AND PROCESS DESIGN

The surveys of Farragher et al. [20] and Hogaboam and Shook [21] concerning capital investment decision-making practices imply that relatively detailed operating cost evaluation is needed to arrive at good forecasts of annual operating cash returns, changes in working capital, and their residual cash flows. This product costing is conducted using mainly traditional volume-based costing, but activity-based costing (ABC) is utilized as well (**Fig. 2**) [22]. ABC is considered a more transparent and accurate costing method due to its capability to properly allocate overhead costs [23-25].

Overhead cost allocation has gained increasing interest in recent management accounting literature [26]. This growing interest results from the need to better respond to marketplace changes and to optimize the manufacturing system for the given product mix. For example, proper overhead cost allocation can reveal the opportunity for alternative use of fixed assets and can steer companies towards an optimized product mix (in oligopoly markets). Thus, using full costs in decision-making, rather than variable costs only (marginal costs), provides a better market response [27].



2. Differences between activity-based costing (ABC) and traditional cost accounting. ABC (left column) assigns the resource costs to activities based on demand, and those activities' costs to the product unit due to the product demands; traditional costing allocates all costs to products based on production amount.

Assignment of joint utility costs also impacts the design analysis. Moreover, the calculation of the utility costs, especially the utility cost (steam) can use several cost assignment bases (enthalpy or entropy difference, electricity generation potential, or exergy [28,29]), and each results in different steam costs. Thus, retrofit implementation changing both the energy system and the joint utility consumption needs rigorous joint cost analysis.

Advanced cost analysis methods have been proposed for process design. Sadhukhan developed a process synthesis methodology for retrofit process design based on value analysis [30,31]. Janssen et al. introduced the utilization of ABC-like cost modeling in a single-product and multifeedstock system retrofit design problem in a mechanical pulping context [32,33]. Varbanov, Perry, et al. [34] and Smith and Varbanov [28] utilized marginal cost analysis in a top-level analysis methodology developed by Makwana et al. [35], calculating the true cost of utilities using the joint cost assignment rule. Sandström investigated the fit between management costing and engineering design, focusing on how the ABC system should be constructed for product costing in process design [36,37]. However, these methodologies have not exploited the full potential of advanced costing, i.e., multiproduct costing. This important aspect of retrofit FBR decision-making is elaborated on in this paper.

RISK ANALYSIS

In process design, several sources of uncertainty exist (model-inherent, process-inherent, external, and discrete) based on their nature [38]. Typically, external uncertainties are considered with the objective of capturing them at design project outset, namely the uncertainties at the company, industry, or general environment levels [39]. The importance of risk analysis in retrofit FBR design project evaluation is clear when contrasted with the case when no risk assessment would be considered, in which case the "implicit assumption is that all projects considered are of equal risk and that risk is the same as the risk for the firm as a whole" [40].

Qualitative and quantitative methods can be used for incorporating uncertainty into techno-economic design analysis. These include subjective methods such as SWOT-analysis (project Strengths, Weaknesses, Opportunities, and Threats) and different scoring methods, as well as deterministic methods such as scenario analysis and sensitivity analysis, and stochastic methods such as Monte-Carlo analysis. According to Hogaboam and Shook's [21] survey, sensitivity analysis and subjective adjustment of cash flows are the most common risk assessment methods used by the forest industry. Systematic methods to account for occurrence probability have not been proposed. Such methods would provide for better screening and ranking of uncertain FBR alternatives.

STRATEGIC INVESTMENT DECISION-MAKING

In a strategic planning process, the mission and drivers, such as global economy, environmental regulations, and resource productivity, influence the company strategy. Strategy is reflected in plans and realized through investment and other programs. Thus, the connection between a single capital investment project and the company strategy is considered to be one directional [41]. Capital investment project appraisal typically follows a five-step process: (1) identification of potential investments, (2) project definition and screening, (3) analysis and acceptance, (4) implementation, and (5) monitoring and post-audit [41-44]. The same appraisal process is often applied to the main types of capital investment projects (infrastructure, strategic, and operational).

Angelis and Lee proposed a methodology for utilizing ABC in a company as a costing method for evaluating cost impacts due to investment strategy on individual activities [45]. Sawhney used activity-based modeling to evaluate investment performance related to manufacturing strategy components (e.g., capacity, productivity, lead time, and quality) [46], and Emblemsvåg [47] or Rivero and Emblemsvåg [48] have used ABC to evaluate life-cycle costs of different long-range scenarios (budgeting scenarios) of a facility or a company. Thus, advanced costing for strategic investment decision-making has been studied by several investigators, but not linked to process design activity.

The investigation by Hogaboam and Shook [21] on performance measure use in U.S. forest industry capital budgeting and rationing concluded that (1) corporate strategic factors, such as potential competitive advantage, or markets, are a key component in strategic investment decision-making, (2) decisions are mainly made based on developed investment goals (strategic and financial), and (3) Internal Rate of Return (IRR) and Net Present Value (NPV) are the main metrics used. Erdhardt and Bringham describe how investors use previous financial statements as the basis for different techniques to capture the relevant viewpoint of their investment (e.g., capability to pay debt and operating or capital efficiency, as well as other valuation methods) [49].

OBJECTIVES

The objectives of this paper are:

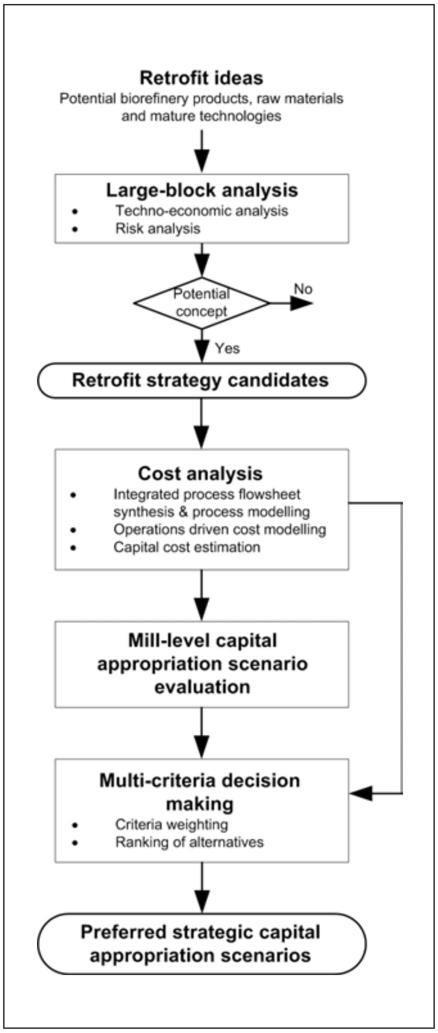
- To elaborate upon a new methodology for strategic retrofit investment decision-making that makes better use of existing process and cost analyses and management accounting activities.
- To demonstrate the methodology's use for decision-making that accounts for project performance and strategic fit, and thus, considers the preferences of many of the company stakeholders. This is done by applying the methodology to a case study of retrofit biorefinery implementation in a North American hardwood kraft pulp and paper mill.

OVERALL METHODOLOGY

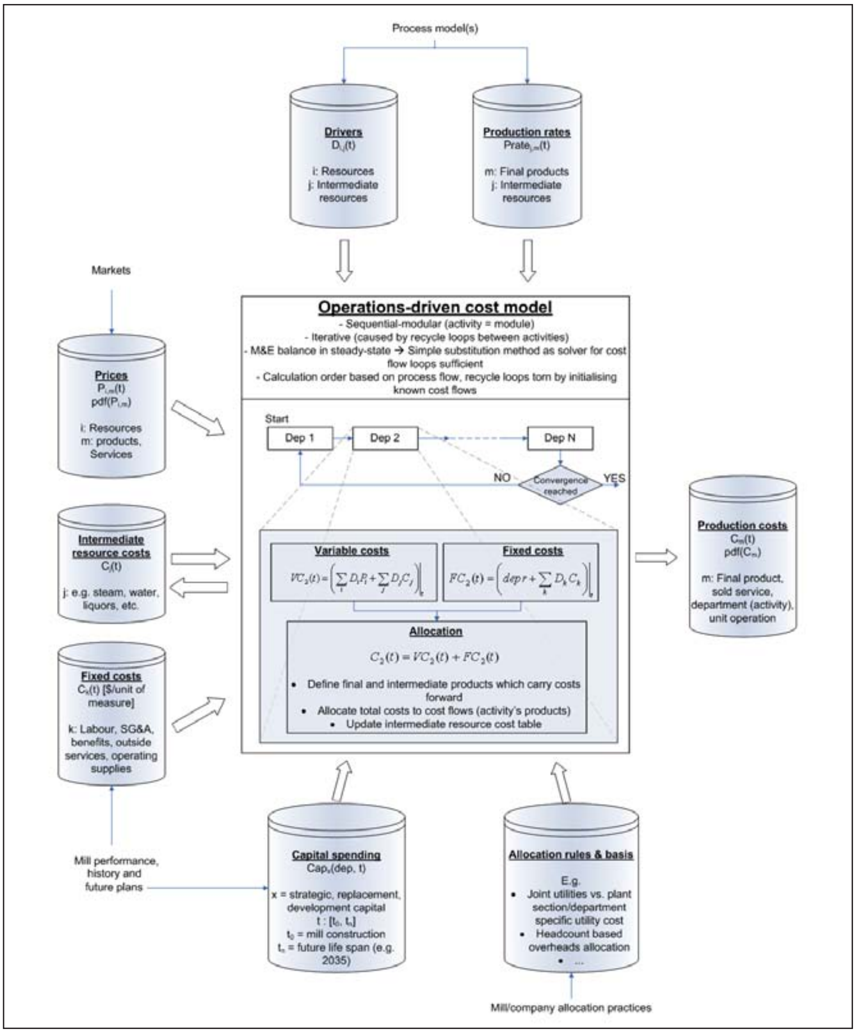
The overall methodology consists of four steps and two decision-making gates. The methodology is illustrated in **Fig. 3**, and the main steps are elaborated on in the following sections.

Large-block analysis

Traditional techno-economic analysis and multivariate stochastic analysis are used as the first step for pre-screening of retrofit FBR processes. In this large-block analysis ([12] provides a detailed description), mass and energy (M&E) balances of the retrofit alternatives are considered using input-output models. Only the new process areas are modeled, and estimated impacts on host process consumption and production rates are credited or added as costs. Monte-Carlo analysis is used for risk analysis and applied at the lowest cost produc-



3. Overall design decision-making methodology.



4. The structure of a cost model for retrofit capital appropriation.

tion capacity of the candidate process designs. The uncertain variables are identified using sensitivity analysis.

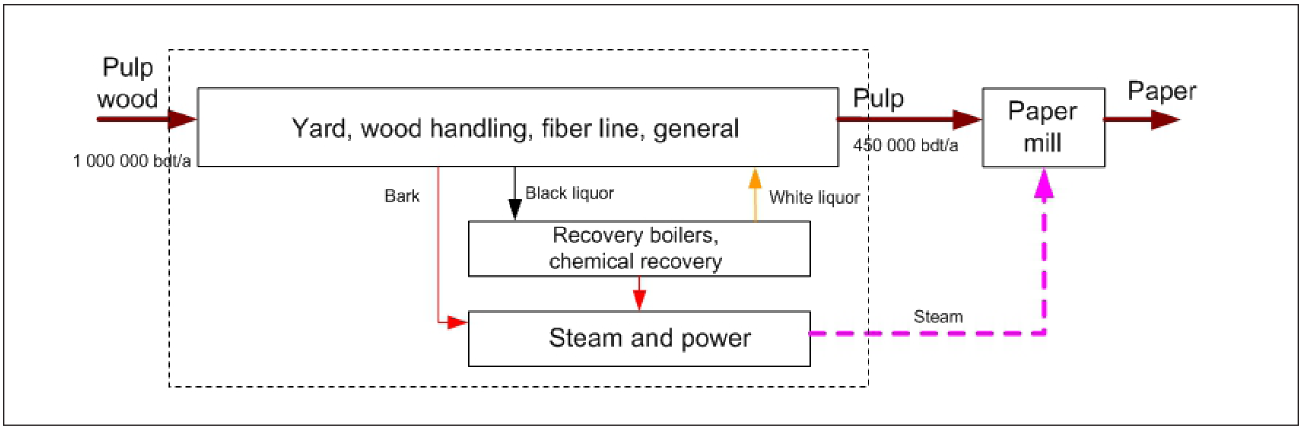
Operations-driven cost analysis

Plant-wide steady-state process simulation models are first developed to define the overall mass and energy balances and retrofit impacts on the existing process conditions and efficiencies. The models can be developed using many commercial simulation software packages. These models are linked to operations-driven cost models that are based on ABC principles. The process models provide cost models with resource and activity driver information. Other key input data of the cost models include mill/company practices of cost allocation, capital spending history, future plans, and other fixed cost rates (e.g., labor rates, sales, general and administrative costs (SG&A), or company overhead rates). These cost models are used for product-costing and *pro forma* cash flow analysis; however, the same models currently used for accounting and periodic reporting could also be used.

A three-step sequence is applied for obtaining accurate cost data: (1) development of the base case process and cost models, (2) validation of the base case models using mill data and financial statements and reports (mill or business unit-level statements and monthly reports are required; publically available financial statements covering all company operations are not suitable for mill-level analysis), and (3) development of the process and cost models of the retained retrofit cases. The resulting cost models convert the process impacts into a better understanding of cost impacts, and into *pro forma* cash flows reflecting expected future facility performance. Monte-Carlo analysis is also used for cash flow uncertainty analysis. **Figure 4** provides a more detailed illustration of the cost model structure.

Retrofit analysis at the mill level

Contextually relevant economic performance criteria and their measures are identified by understanding the key performance factors and the business environment. Examples of these key factors are product cost breakdowns; cost competitiveness; location-specific uncertainties in the business envi-



5. Base-case mill block diagram and system boundary (dashed line).

ronment, such as feedstock and product markets; and criteria for capital performance that stakeholders and investors use in investment decision-making. The measures are evaluated based on the *pro forma* cash flow statements calculated using the operations-driven costing.

Multicriteria decision-making

A multicriteria decision-making (MCDM) method is applied for obtaining the attribute preferences (weights) for the identified criteria. Multiattribute utility theory (MAUT) was used as the MCDM method, and a panel-based tradeoff technique was selected for the weighting because it is easy to understand and implement. In the tradeoff process, the panel members compare each criterion to the most important criterion selected by the entire panel. Comparisons are made as tradeoffs: the panelist estimates an attribute score of the most important criterion that makes him/her feel indifferent to the other criterion at its maximum score. These tradeoffs were assumed to be valid through the ranges of attribute values; thus, the criteria are mutually preference independent in the analysis context. Furthermore, the utilities developed from the tradeoff values were assumed to be linear between the attribute boundaries, reflecting risk-neutrality of the decision-making panel. The average and the standard deviations of the relative importance of all criteria are obtained as a result.

CASE STUDY

Base case pulp and paper mill

Integration of a biorefinery into a North American hardwood kraft pulp and paper mill was considered as the case study. The studied mill is part of a large pulp and paper company with production facilities located in North America. The mill produces woodfree coated papers from kraft pulp produced on-site. In the study, only the kraft pulp mill and utility systems are considered because the retrofit integration affects only these and not the paper mill (**Fig. 5**).

Retrofit process alternatives

In the first design stage of the methodology (large-block analysis), a comparison of different potential retrofit alternatives is made. For this purpose, we identified potential alternatives with the case mill. Different raw material types suitable for the biorefinery are available to the mill, and potential end users for the bioproducts are in the vicinity. A total of 42 feedstock-process-product combinations were initially identified as potential retrofit alternatives for pre-screening. These alternatives used as feedstock hemicelluloses or lignin (tightly integrated FBR concepts), or woody biomass, pulpwood, corn, corn stover, or food processing wastes (adjacent integrated FBR concepts). The processes were thermochemical (high temperature gasification or steam reforming routes to synthesis gas [syngas] followed by mixed alcohols [MA] or FTL synthesis or syngas fermentation) and biochemical (enzymatic or acidic hydrolysis followed by fermentation to ethanol). The products were bioethanol, MA, and FTL for fuels or waxes. The process designs were developed based on publically available data, and more detailed descriptions of the process designs and their development have been published elsewhere by the authors [11,12].

Project profitability and downside project profitability using after-tax IRR as measure and decision-makers' preferences of technology and market maturity were used as screening criteria. The resulting set of promising retrofit alternatives for the case study mill are described in the results section.

Economic assumptions

Our price and economic scenario assumptions are based on recent historical U.S. values (**Table I**). In addition to the price development in the scenario shown in the table, the future inflation rate was assumed to be 3.7%. A labor cost increase of 0.25%, labor productivity increase of 0.5%, and pulp production reliability increase of 0.25% annually was also assumed. Moreover, we estimated annual capital expenditures from historical case pulp mill investment budgets using Chemical Engineering Plant Cost Index (CEPCI) with a division of 25/75 to development and replacement investments and assuming two years payback time for development investments. Depreciation was calculated using linear depreciation (power and recovery area 20 years, other process types 10 years) and a 40% tax rate was used.

	Price Assumption	Economic Scenario Assumptions Related to Prices
Feedstock	Supply curves of all feedstocks presented by the authors in [11]	Forest and agro-residue crop – 2.5% annual increase in addition to inflation (expected increase in competition)
Energy	Electricity – $61/MWh Coal – $40/ton Natural gas – $5.6/MJ	Prices follow inflation
Chemicals	H_2SO_4 – $120/ton NaOH – $650/ton Lime – $100/ton Oxygen – $63/ton Enzymes – $0.033/kg ethanol (corresponds to 0.1$/gal ethanol)	Prices follow inflation
Products	Ethanol and mixed alcohols (MA) – higher heating value (HHV) corrected gasoline Fischer-Tropsch liquids (FTL) – diesel retail price Distillers dry grind with solubles (DDGS) – $0.1/kg Furfural – $0.33/kg Acetic acid – $1.17/kg Pulp – $650/ton (transfer price, adjusted from market pulp price)	Oil price (affects gasoline and diesel price) – 2% annual increase in addition to inflation Pulp – 0.5% annual decrease

I. Price and economic scenario assumptions (prices in US$).

Feedstock, Product (Process)	Capacity (ML/year)	IRR (%)	Standard Deviation (%)	Downside IRR (%)
Corn stover, mixed alcohols (steam reforming)	379	13.0	2.1	8.7
Lignin, ethanol + higher alcohols (steam reforming)	189	12.3	2.0	8.2
Biomass, mixed alcohols (steam reforming)	95	8.7	1.6	5.5
Hemicelluloses, ethanol + acetic acid (near-neutral hemicellulose extraction prior-to-pulping)	19	6.9	0.9	5.0
Biomass, ethanol + higher alcohols (steam reforming)	95	5.9	1.5	2.9
Corn stover, ethanol + higher alcohols (steam reforming)	379	3.4	2.0	-0.6
Pulpwood, mixed alcohols (steam reforming)	189	3.4	7.3	-11.1
Lignin, ethanol + higher alcohols (gasification)	189	1.5	3.3	-5.1
Corn stover, mixed alcohols (gasification)	379	0.7	3.4	-6.0
Biomass, FTL (gasification)	95	0.6	2.1	-3.5

II. Most promising design alternatives based on ranking using internal rate of return (IRR).

RESULTS AND DISCUSSION

The main results from the case study application of the overall methodology are discussed in the following sections; more details of individual analysis steps and results can be found from [11,12] for the pre-screening, from [50,51] for the operations-driven cost modeling, and from [52] for the investment decision-making.

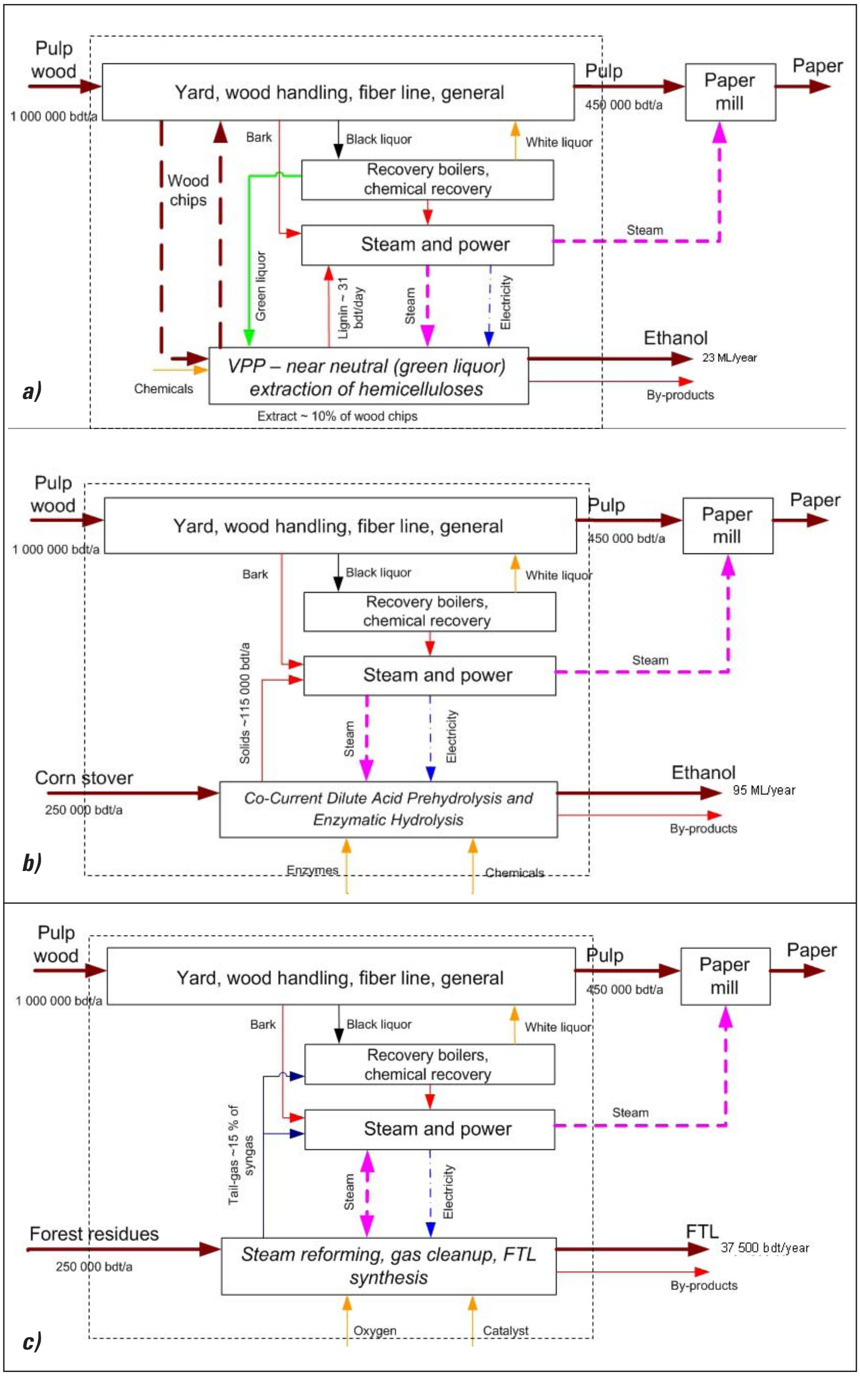
Retrofit project pre-screening

First the production and investment costs and project profitability of the identified 42 retrofit alternatives as a function of design capacity were estimated. Mass and energy balances were developed based on literature design studies (references and details in [11,12]) using Microsoft Excel. We selected the lowest production cost designs of all alternatives (10% capital recovery factor used to account for the capital costs) and conducted a sensitivity analysis. Based on the sensitivity analysis, the key uncertain factors were fossil fuel, electricity, and feedstock prices; inflation; and future fuel and feedstock price trends. Probability distributions for uncorrelated uncertain external factors were then developed using publicly available data. Normal distribution was used for all trend uncertainties. Moreover, different distributions were developed from historical real price data to represent volatility around the trend. (Details can be found in [50].)

The alternatives considered in the pre-screening were all at a relatively high technology development level and the markets for the products exist. Therefore, process and market maturity-based uncertainties could be excluded from the pre-screening without affecting the relative order of the alternatives.

We used Monte-Carlo analysis for risk analysis (5000 cash flow series iterations). After-tax IRR was used as profitability measure. Based on the results, some of the alternatives are not profitable under the economic assumptions and can be screened out from further analyses. The risk measure used was downside project profitability (expected value minus two times standard deviation, or after-tax IRR obtained with 97.5% certainty), which is generally considered a significant metric for strategic investment decision-making in manufacturing industries [40]. The resulting list of the most promising retrofit projects is presented in **Table II**. The projects are ranked based on expected risk-free project profitability.

When comparing this ranking and the relative risk in each of the retrofit projects (represented as the standard deviation), it is clear that the most promis-



6. Block diagrams of retained retrofit biorefinery alternatives, production figures of base case mill implementation: (a) hemicellulose extraction prior-to-pulping (VPP), (b) corn stover-to-ethanol, and (c) woody biomass-to-FTL.

	Retrofit Alternatives								
	Base Case	Mill Mod.	VPP	Small FTL	Large FTL	Small EtOH	Large EtOH	Small FTL (wax)	Large FTL (wax)
Input Process Variables									
Green wood including bark (ton/day)	7500	9700	7500 /9700	7500 /9700	7500 /9700	7500 /9700	7500 /9700	7500 /9700	7500 /9700
Biorefinery feedstock (o.d. ton/year)	-	-	88000 /126000[a]	250000	1000000	250000	1000000	250000	1000 000
Energy Inputs (MW)									
Black liquor to recovery boilers	218	286	192 /265	218 /286	218 /286	218 /286	218 /286	218 /286	218 /286
Bark and screening losses to power									
Boiler	100	124	100 /124	100 /124	100 /124	100 /124	100 /124	100 /124	100 /124
Coal to power boiler	120	98	105 /129	78 /98	9 /98	78 /98	105 /150	95 /98	17 /98
Natural gas to power boiler	17	0	95/0	0	0	47/0	0	0	0
Syngas to power boiler	-	-	-	22 /17	170 /165	-	-	22 /17	170 /165
Biomass solid residue to power boiler	-	-	-	-	-	43	147	-	-
Natural gas to lime kiln	27	32	21 /22	0	0	27 /32	27 /32	0	0
Syngas to lime kiln	-	-	-	27 /32	27 /32	-	-	27 /32	27 /32
Pulping process electricity demand	40	48	40 /48	40 /48	40 /48	40 /48	40 /48	40 /48	40 /48
Biorefinery electricity demand	-	-	0.2/0.25	12.7	50.7	1.9	7.5	14.3	57
Pulping steam demand [b]	250	306	239 /266	237 /303	256 /341	243 /308	289 /328	243 /311	256 /342
Biorefinery steam demand [c]	-	-	63/78	12.5	50	34	135	12.7	50.4
Output Process Variables									
Pulp production (/day)	1220	1650	1220 /1650	1220 /1650	1220 /1650	1220 /1650	1220 /1650	1220 /1650	1220 /1650
Electricity production (MW)	40	84	40/69	45/95	89/162	45/88	79/99	40/88	74/160
Bioproduct production rate									
(ML/year - EtOH, o.d. ton/year - FTL)	-	-	23/30	37500	150000	95	380	37500	150000
Water to treatment plant (m^3/day) [d]	52300	55700	57500 /67000	52700 /60400	67600 /82400	55000 /59800	67700 /68800	54000 /62500	68000 /88900

[a] Includes organic and inorganic material.

[b] Includes low pressure (LP) (60 psig) and medium pressure (MP) (160 psig) steam demand of pulp mill and power plant; base case steam network not optimized (vent steam losses included in process steam); extraction steam consumption allocated to biorefinery.

[c] Includes LP (60 psig) and MP (160 psig) steam.

[d] Includes pulp mill and forest biorefinery waste water.

III. Performance estimates of retrofit alternatives and the base case mill based on process simulation models. Performance estimates are given for (a) base case and (b) modernized mill retrofit cases and are separated by a slash.

ing alternatives have higher risk than some of the lower profitability options. Moreover, some of the projects have significantly higher risk even though the same technology and products are considered. This results from different feedstock cost uncertainties. We used this knowledge in screening out higher risk retrofit alternatives, in addition to low-performance alternatives.

The retained biorefinery designs after pre-screening are presented in **Fig. 6**. Figure 6a shows the VPP process (near-neutral green-liquor extraction, acidic hydrolysis, liquid-liquid separation, fermentation, and distillation) to produce ethanol and furfural. Figure 6b shows corn stover co-processed with kraft pulp using mill infrastructure to the maximum extent (dilute acid pre-treatment, enzymatic hydrolysis, fermentation and distillation, solid residue burned in power boilers) to produce ethanol. Figure 6c shows forest residues coprocessed with kraft pulp using mill infrastructure to the maximum extent (drying and grinding, steam reforming, gas cleaning and compression, FTL synthesis, and FT wax separation) to produce FTL for fuel, or waxes and diesel fuel.

In addition to the biorefinery retrofit alternatives, a pulp mill modernization project identified by the case mill was included in the analysis. This modernization would increase pulp production capacity by 35% and update many of the utility systems, including installation of a new recovery boiler and a condensing turbine, and retrofitting of power boilers. Also, a new lime kiln would be implemented and the fiber line would be retrofitted.

Retrofit project cost-impact analysis

The process simulation models were constructed for analysis of the retained retrofit alternatives. We used BALAS process simulation software (VTT Technical Research Centre of Finland; Espoo, Finland) in the process modeling.

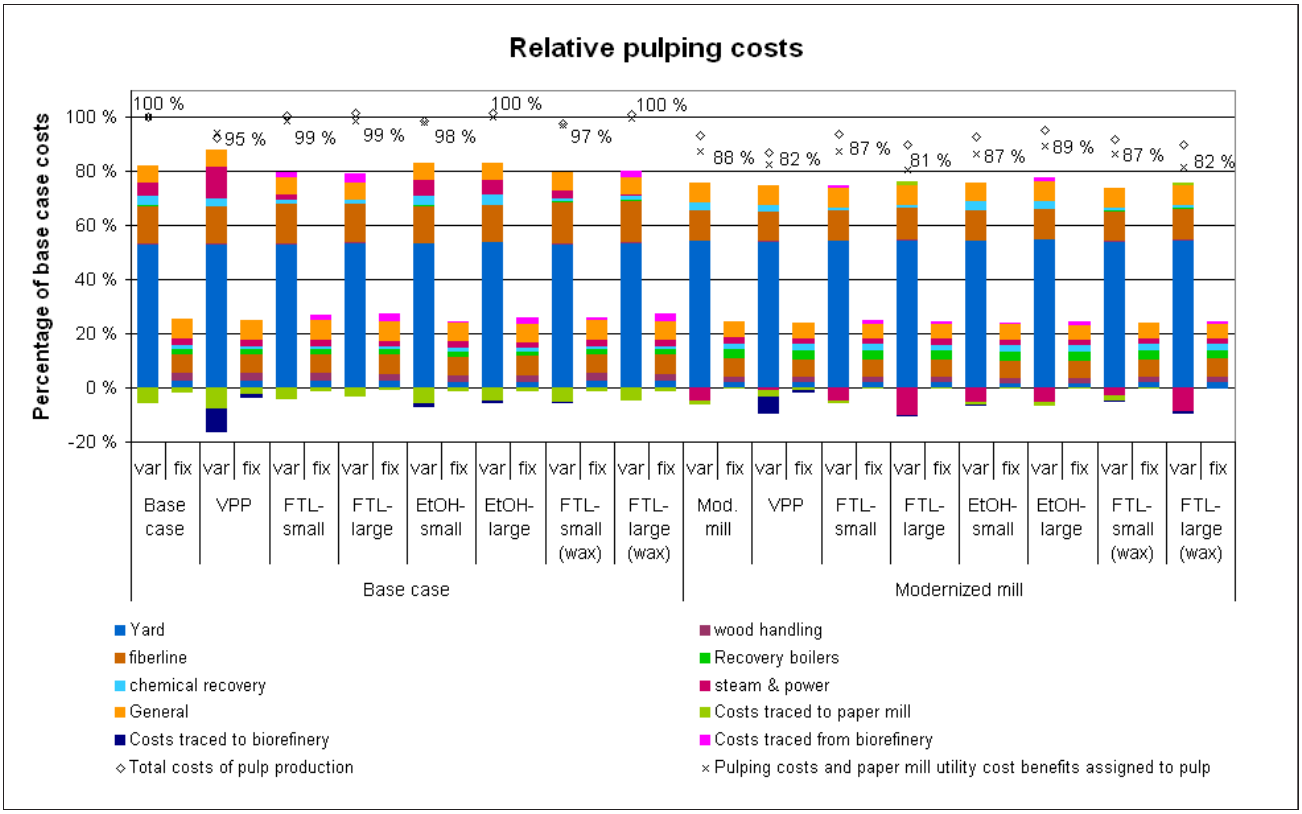
Table III compares the performance measures of the retrofit alternatives based on the process simulation. Production rates of products and consumption of energy are shown. The base case process simulation model was validated using process data obtained from the mill data management system.

Capital investment cost estimates were developed using

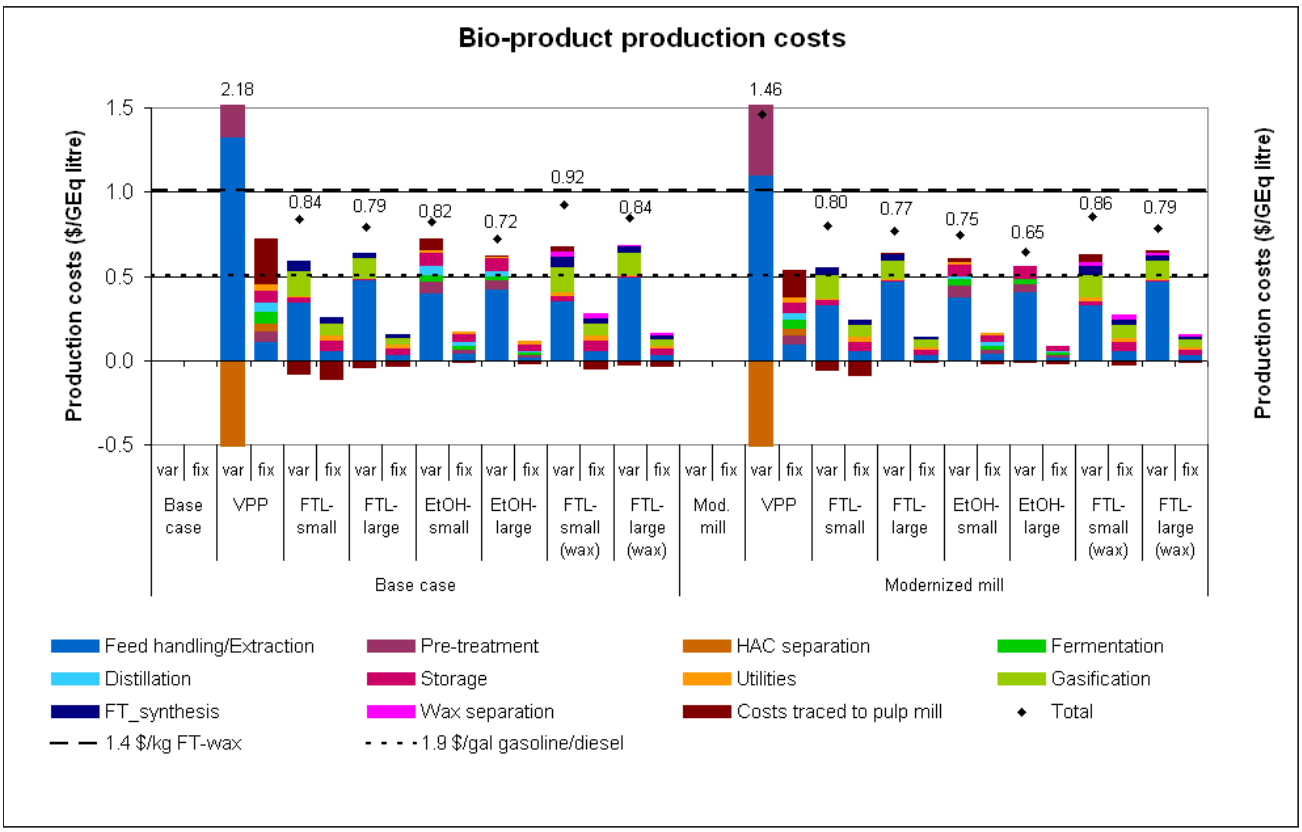
	Retrofit Alternatives							
	Mill Mod.	**VPP[b]**	**Small FTL[c]**	**Large FTL[c]**	**Small EtOH[d]**	**Large EtOH[d]**	**Small FTL (wax)[c]**	**Large FTL (wax)[c]**
Equipment Costs ($M)								
Pulp mill[a]	230	-/230	-/230	-/230	-/230	-/230	-/230	-/230
Feed handling/extraction	-	16/19	24	66	5	12	24	66
Pre-treatment	-	7/8	-	-	17	45	-	-
Acetic acid separation	-	2.3/2.7	-	-	-	-	-	-
Fermentation	-	7/8	-	-	6	16	-	-
Distillation	-	5/6	-	-	14	37	-	-
Gasification	-	-	42	104	-	-	42	104
FTL	-	-	14	39	-	-	14	39
Wax separation	-	-	-	-	-	-	11	32
Storage	-	0.5/0.6	2	4	1	3	3	8
Utilities	-	1.0/1.2	13	32	3	74	13	32
Total installed								
equipment (TIC)	230	38/276	95/325	245/475	47/277	188/419	107/337	281/511
Added Costs ($M)								
Indirect (5% from TIC)	12	1.9/14	5/16	12/24	2/14	9/21	5/17	14/26
Contingency (15% of TPI)	43	7.1/51	18/60	45/88	9/51	35/78	20/63	52/95
Total ($M)								
Total project								
investment (TPI)	284	47/341	117/401	303/587	58/342	233/517	133/417	347/631

[a] Case study mill estimate.
[b] [1]
[c] [53,54]
[d] [55]

IV. Capital investment cost estimates of retrofit alternatives (values are given in millions of US$). Single value represents the investment cost of both base case and modernized mills; otherwise, cost estimates in the two pulp mill cases are separated with a slash.



7. Variable and fixed pulp production costs in retained retrofit alternatives.



8. Variable and fixed bioproduct production costs in retained retrofit alternatives.

Design Alternative (Integrated into Base Case Mill)	Traditional Analysis ($/L Geq)	Operations-Driven Cost Analysis ($/L Geq)[a]
VPP	0.69	1.3
Small FTL process	0.59	0.77
Large corn stover-to-ethanol process	0.55	0.72

[a] Pulp and paper production cost benefits relative to base case are assigned to biofuel production costs for commensurate comparison.

V. Comparison of traditional costing and operations-driven costing: Biofuel production costs in selected retrofit alternatives. Costs are measured in dollars (US$) per gasoline equivalent (Geq) liter.

publically available values converted to 2010 dollars (US$) and scaled to design capacities with an exponential scaling equation (exponent 0.65-0.75, capacities of main process equipment from M&E balances). Our cost estimates of the alternatives are shown in **Table IV**.

Next, the cost models were developed for each retrofit alternative. Impact:ECS Enterprise Cost System (3C Software; Atlanta, GA, USA) was utilized. The simulation model-based mass and energy balances of different retrofit alternatives were converted to resource and activity driver tables in the cost models, and data were transferred using Microsoft Excel Furthermore, the base case production costs were validated using monthly pulp mill financial statements/reports from the simulation model input data period.

The cost impacts of the retrofit alternatives on pulp production are shown in **Fig. 7** (including all added cost or benefits realized at the integrated paper mill). They varied between a 0.2% increase and a 19.2% decrease, measured from the base case production costs. Thus, significant cost changes resulted from retrofitting, and the largest cost reduction was obtained in simultaneous mill modernization and biorefinery implementation, resulting mainly from the additional capacity in all energy systems (boilers, turbines) and increased electricity production due to better energy efficiency.

The bioproduct production costs (**Fig. 8**) in the same retrofit alternatives show that even though the feedstock costs are the main contributor to the total biofuel production costs, both variable and fixed costs transferred between the pulp mill and biorefinery activities impact total costs significantly.

Energy costs are an important factor for good economic performance of the forest biorefinery, and these costs vary significantly between retrofit alternatives. Three factors (steam demand, available fuel mix, and energy system constraints) define most of these costs. The combined effect of them is partly illustrated in Fig. 7. Costs of the steam and power department are shown as varying from ~10% of the reference pulp production costs to ~10% of the revenue (measured as percentage of reference pulp production costs), and as costs traced to the paper mill (consisting mainly of energy costs/revenues).

Comparing the production costs of biofuels between the large-block analysis and the advanced costing, we obtained different results (**Table V**). These differences result from the assumptions used in energy cost calculation. In the cost-impact analysis using advanced costing, the case mill boiler and turbine efficiency curves were incorporated into the simulation models, and realistic constraints in each steam demand condition were considered. In traditional analysis, the constant steam cost assumption led to overestimating the energy system potential and, therefore, underestimating the bioproduct production costs. A second reason for the differences is that no additional workforce was assumed to be required in the traditional analysis, whereas in the analysis using the developed costing framework, the available workforce at the mill was systematically assessed and extra labor was considered to be used when needed. Thus, the level of detail used in traditional techno-economic analysis for strategic investment decision-making might not be sufficient.

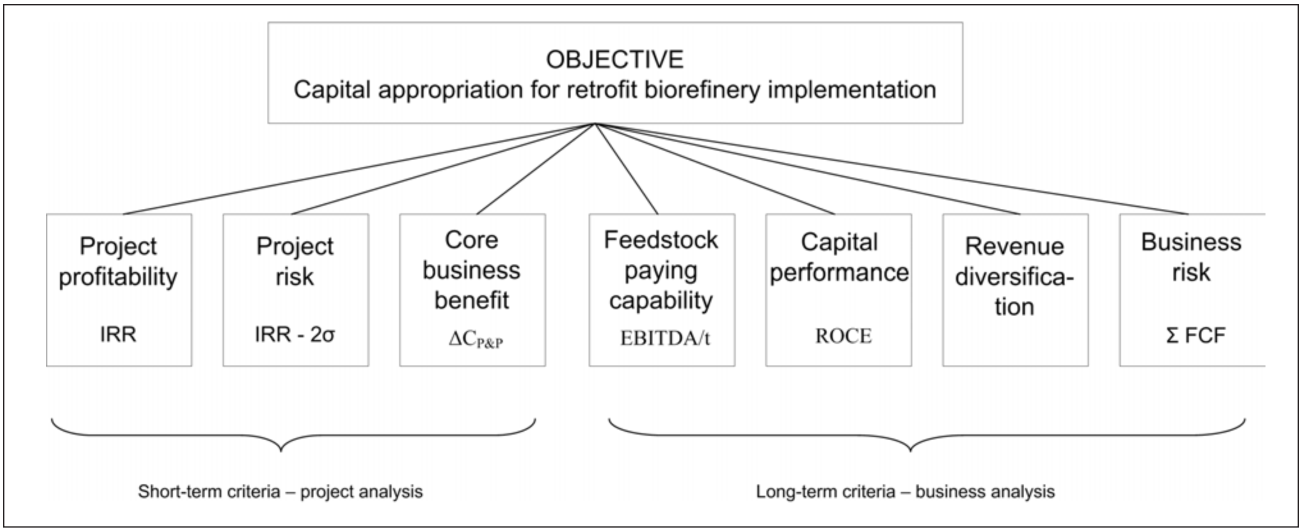
Capital appropriation decision-making

First, the set of independent criteria for strategic investment decision-making and the metrics for these criteria were identified. The set of criteria is presented in **Fig. 9**, along with the criteria measures.

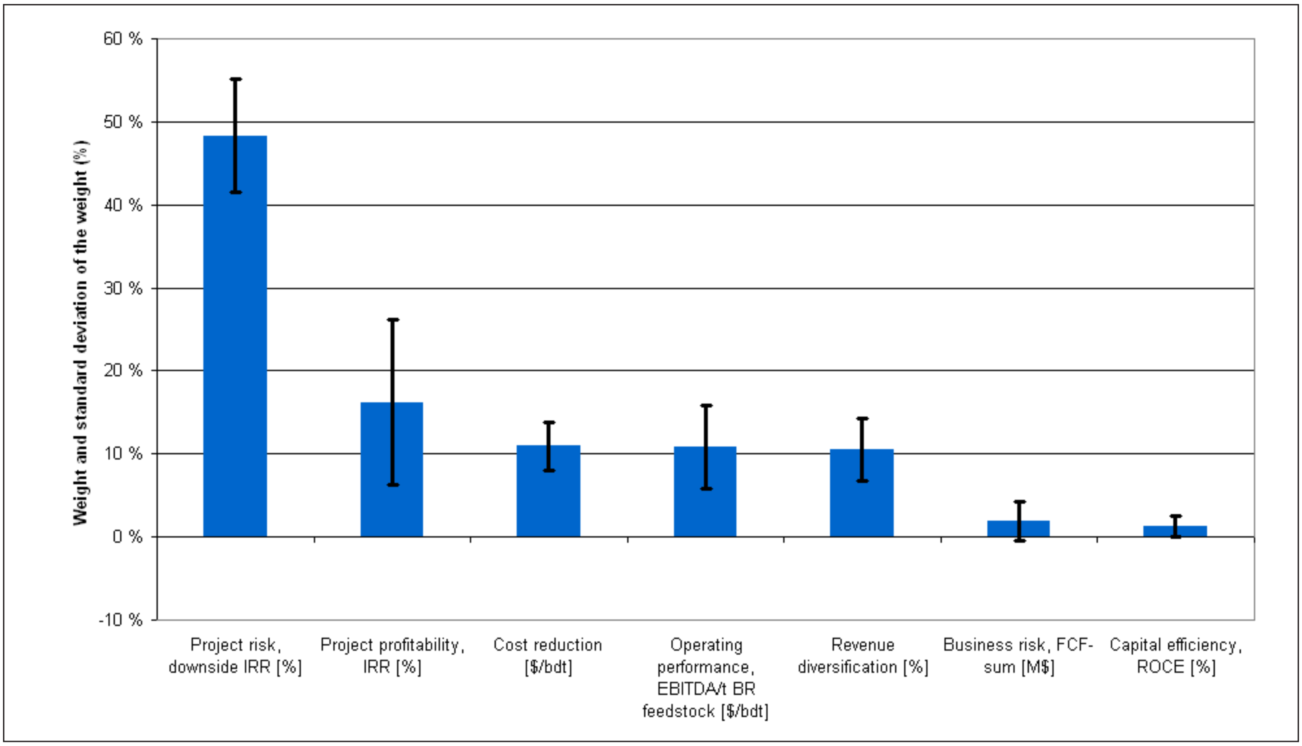
Eight people from the case study mill (including the mill manager, process engineers, research and development, and strategic planning personnel) involved in investment decision-making were assembled for an MCDM panel. In the panel-based tradeoff MCDM, all panelists were given an equally important role in the decision-making. **Figure 10** shows the resulting decision weights, based on average tradeoff values of the panel and the standard deviation in the weights resulting from sensitivity analysis (Monte-Carlo analysis, probability distributions fitted to panelists' tradeoff values for each criterion).

The project performance criteria (three highest ranked criteria) constituted over 75% of the total weight. Moreover, for the panelists, the capital efficiency and capability to respond to unexpected drastic changes in the business environment by reinvestments and new strategic investments had very little weight. This reflects both the company practices, and possibly, the panel orientation towards short-term decision-making.

Utilizing the weights and the evaluated attribute intensi-



9. Decision structure for the retrofit design problem. IRR – internal rate of return; σ – standard deviation; ΔCP&P – core business product cost change; EBITDA – earnings before interest, taxes, depreciation and amortization; ROCE – return on capital employed; ΣFCF – sum of free cash flows.



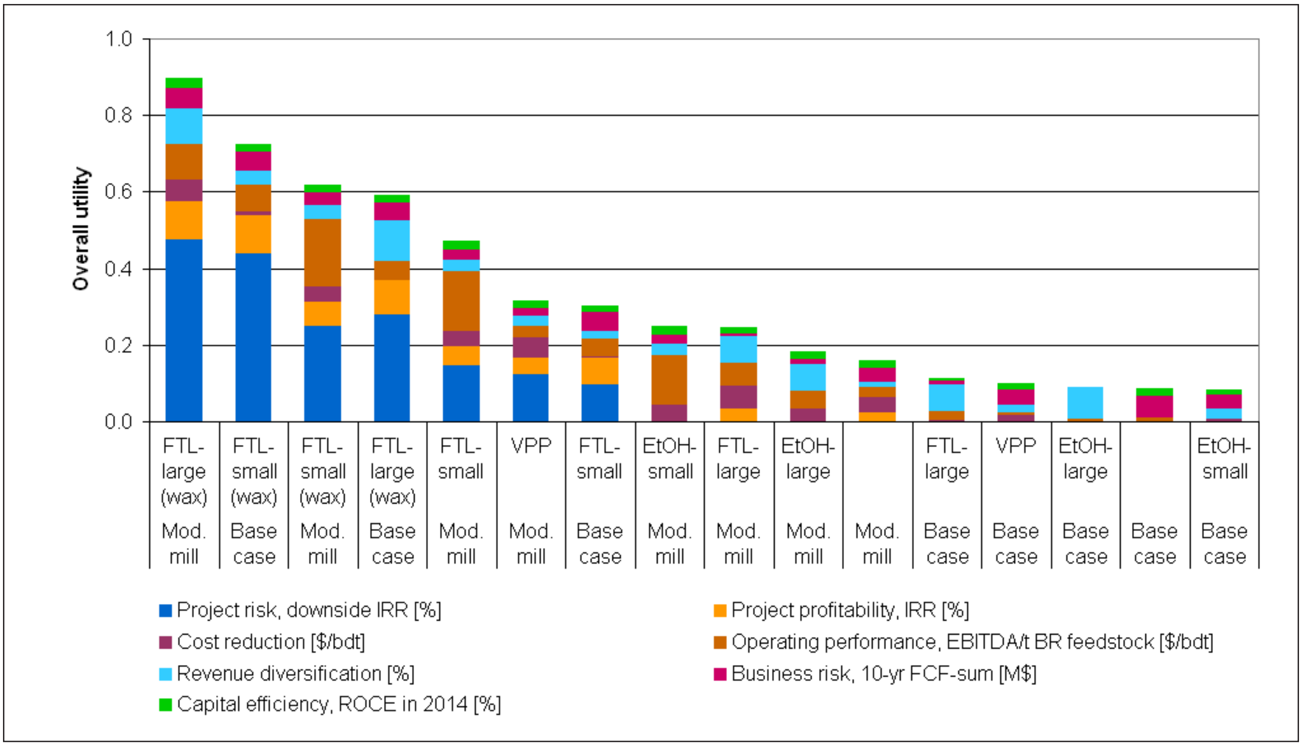
10. Decision weights based on average tradeoff values and their standard deviations calculated using Monte-Carlo analysis.

ties, the overall utility is obtained using an additive utility function.

$$U(x) = \sum_i w_i u_i(x_i) \tag{1}$$

where $U(x)$ is the total utility, w_i is a weight of the attribute i, and $u_i(x_i)$ is the utility of the attribute i. The summation goes through all decision-making attributes i. This overall utility represents the ranking of the alternatives (**Fig. 11**).

The most important criterion dominates the ranking. Between the most preferred alternatives, a more balanced decision where all criteria contribute to the overall utility can be seen. The overall ranking follows the ranking based on project-based criteria, except in the case of the third and fourth most preferred alternatives where good operating performance of the third alternative emphasizes the importance of



11. Ranking of capital investment alternatives based on overall utility value.

strategic performance criteria. On the other hand, for the lower ranked alternatives with less balanced overall utilities, differences between impacts of individual strategic criteria on overall ranking are significant.

CONCLUSIONS

The capital intensity of the pulp and paper and biorefinery processes are important factors for forest biorefinery decision-making. Moreover, the relatively low capital efficiency of the pulp and paper industry compared to other capital-intensive manufacturing industries makes this industry unattractive to investors [56] and can potentially hinder decision-making for the forest biorefinery. This, combined with the uncertain forest biorefinery business environment, makes it critical to apply systematic risk analysis and an effective decision-making process.

Often, higher returns are expected from higher risk investment projects. Subjective discounting is commonly used when analyzing economic performance of potential investment projects in the forest industry. Moreover, different scoring-based investment opportunity analyses, including subjective risk terms, are applied to account for technological and market risks. Thus, risk analysis is recognized to be important, but different sources of uncertainty have not been systematically considered in forest biorefinery decision-making.

Therefore, the objective of this work was to develop a methodology to improve the link among retrofit process design, cost accounting, and capital investment decision-making to enhance the decision-making process when considering and implementing a forest biorefinery retrofit under uncertain conditions. The methodology consists of stepwise decision-making, starting with pre-screening of retrofit design alternatives based on traditional techno-economics and risk analysis, followed by an advanced decision-making procedure. The second decision-making step uses a novel framework combining process design and simulation with strategic investment decision-making through cost accounting models based on activity-based costing principles. The operations-driven cost models that are linked to process simulation are able to represent accurately the manufacturing costs of all products after the retrofit biorefinery implementation. On the other hand, these models are able to provide useful and accurate financial data for strategic investment decision-making by supplying measures of short- and long-term performance of the retrofit alternatives and the facility overall. Moreover, systematic risk analysis using stochastic multivariate analysis can be utilized since all performance metrics are explicitly quantified.

Results of the methodology application in the case study showed that systematic analysis of the impacts of external uncertainties using multivariate stochastic analysis enables a more objective assessment of retrofit alternatives. Furthermore, the analytical results of the retrofit design alternatives, when studied in detail using the developed operations-driven costing framework, clearly quantified the cost impacts of the retrofit projects, which in the case of normal process design and capital appropriation would be available only for the implemented project when it is operating. These impacts varied between alternatives because of different integration potential and system constraints. Assessment of the importance of key performance criteria using a panel-based MCDM showed that even though project performance criteria were preferred, facility-level performance had an important role in the overall ranking of the retrofit alternatives. Moreover, the final ranking of the alternatives differed from that of using only a single criterion, project profitability. The results shown are valid only in this case mill context. **TJ**

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ABBREVIATIONS

ABC	Activity Based Costing
CEPCI	Chemical Engineering Plant Cost Index
EBITDA	Earnings Before Interest, Tax, Depreciation, and Amortization
EtOH	Ethanol
FBR	Forest Biorefinery
FCF	Free Cash Flow
FTL	Fischer-Tropsch Liquids
HHV	Higher Heating Value
IRR	Internal Rate of Return
MA	Mixed Alcohols
MAUT	Multiattribute Utility Theory
MCDM	Multicriteria Decision-Making
NPV	Net Present Value
O&M	Operations and Maintenance
P&P	Pulp & Paper
ROCE	Return on Capital Employed
SWOT	Strengths, Weaknesses, Opportunities, Threats
SG&A	Sales, General and Administrative
VPP	Value Prior-to-Pulping
σ	Standard Deviation

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ABOUT THE AUTHORS

While many companies are establishing strategic plans for transforming their core businesses to incorporate biorefining, forest biorefinery implementation is occurring slowly. Currently, various methods are employed by companies to analyze process and business characteristics and predict the impact of uncertainties on biorefinery product and process options, including advanced cost accounting methods and group decision-making. However, a systematic link among these varying activities rarely exists.

To address this issue, we developed a methodology to assist the investment decision-making processes involved when mills are considering and implementing a biorefinery retrofit. In this paper, we demonstrate the usefulness of this methodology by presenting a case study at a kraft pulp and paper mill. The results show that systematic analysis of external uncertainties can provide more objective decision-making information about worst-case scenario performance during the pre-screening stage. Furthermore, we found that the cost impact of retrofit biorefinery projects on core business production costs can vary significantly between alternatives due to integration potential and other system constraints. A multicriteria decision-making (MCDM) panel was held to rank biorefinery design alternatives using information related to worst-case scenario performance, and it was found that this information was preferred by panelists relative to using only classical project profitability information.

The overall methodology applied to the case study effectively narrowed a large number of biorefinery retrofit alternatives down to a more manageable set of process-product combinations at the early design stage. This was achieved by systematically linking different analysis capabilities to assist in investment decision-making.

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