AN INTEGRATED TACTICAL PLANNING MODEL FOR MARGINS-BASED OPERATIONS IN THE FOREST BIOREFINERY

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Abstract

The biorefinery is generally recognized as a promising solution to transform the forestry industry. From a company perspective, at least two important decision-making elements need to be addressed: what is the best biorefinery configuration in terms of product/process portfolio, supply-chain network, capacity and manufacturing flexibility, and, for a defined biorefinery configuration, what supply-chain policies should be developed for achieving highest profitability in different market scenarios. In this paper, an integrated tactical planning model that can be used to help designing and managing forest biorefineries is presented. Test case results show that the model formulation is flexible enough to represent different biorefinery strategies and is fast enough to test several scenarios in an acceptable time.

Keywords

Forest Biorefinery, Supply-Chain Management, Margins-based Planning

Introduction

The forestry industry of North America has been facing a difficult economic situation recently. To exit this stalemate situation, some major companies have shown increasing interest in the biorefinery concept.

While the transformation to the biorefinery appears as a promising solution, several strategic changes in the business model and manufacturing culture are nonetheless needed. The biggest challenge for this industry will be to move away from the commodity business mentality (Thorp, 2005). Traditionally, the forestry industry views process efficiency as the key for low-cost manufacturing and profitability. However, using this strategy, other supply-chain costs are often ignored, resulting in lesser profit especially in difficult and changing market conditions (Dansereau et al., 2009; Feng et al., 2008). In a transformed biorefinery business, producing high volumes of undistinguished products with low margins will not be sustainable. Bioproducts will likely face market volatility as they will replace or substitute traditional fossil-based commodities. At the same time, biomass prices will increase as the demand for new bioproducts grows. Hence, biorefineries will have to deal with significant margin pressure on both the sales and procurement sides.

Companies should seek to maximize their margins over the overall supply chain (SC), even if it implies higher manufacturing costs due to increased grade/product changes. In this context, opportunities for allocating capacity to the most profitable sales following revenue management principles should be taken (Talluri & van Ryzin, 2004). Flexibility in manufacturing processes should also be designed and exploited to manufacture more or less products according to market price volatility. This transformation could imply important supply chain restructuring inside the company. For instance, advanced costing methods could be used to understand true operating margins by breaking down costs, thus enabling an evaluation of the trade-offs between different operating regimes, products/grades and/or capacity levels. Integrated

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planning, from procurement to sales but also between the various installations of the company, will be critical to address the overall profitability of the firm. In brief, operating a company in a margins-based fashion goes back to elaborating new SC policies that will dictate the way the whole company operates in different market environments: which sales to fulfill, production throughput and recipes, product changeovers, inventory levels, etc. Production capacity however cannot always be attributed to the most profitable sales as one would see fit. For instance, a large part of the demand in the process industry is secured under contracts, and the decision of accepting/rejecting sales cannot be done at the order level.

Regarding the design of the biorefinery, selecting the right product portfolio as well as its associated technologies and capacities poses a major challenge on a company's point of view. (Mansoornejad et al., 2010) proposed a hierarchical methodology for designing the product/process portfolio and SC network of a forest biorefinery. In this framework, interesting product/process portfolios are first identified based on a market analysis. These options are then analyzed through a large-block analysis in order to screen out the non-profitable ones. Additional environmental (life cycle analysis) and SC-based analysis are performed on the refined set of portfolios to evaluate them in terms of different aspects. The outputs of these two analysis can then be used in a multi-criteria decision making framework to assess the most sustainable product-process portfolios. This step-wise approach enables the systematic consideration of supply chain aspects at the early-stage design of the biorefinery.

The objective of this paper is to present an integrated tactical planning model that can be used for two purposes: for the SC analysis of different forest biorefinery strategies, and for the development of margins-based SC policies for targeted biorefinery product/process portfolios in different market scenarios. The paper is structured as the following. Key aspects that should be considered in a planning model are first identified. Then, a description of the modeled SC and of the mathematical formulation is made, followed by a worked example of an application to an existing forestry company. Finally, important elements of decision-making related to the biorefinery that can be addressed by such formulation are discussed.

Forest Biorefinery Problem Definition

For being able to address the design and management of flexible margins-oriented forest biorefineries, the following aspects should be taken into account in a model. Biomass procurement is limited per location and over the year. Several capacity-constrained suppliers/harvesting locations offer different types of raw materials (e.g. wood species) at different prices depending on the season. At the process level, energy balances, as well as throughput and recipe flexibility modeling capabilities should be included for representing different ways of production. Biorefining and forestry processes can be great consumers of steam and/or electricity. It is therefore crucial for new retrofitted biorefineries to take the energy infrastructure in consideration. Costing should be developed using a bottom-up approach to better represent the margins of different products and recipes. Finally, modeling of sales and demand should allow customer segmentation to open the floor for revenue management principles.

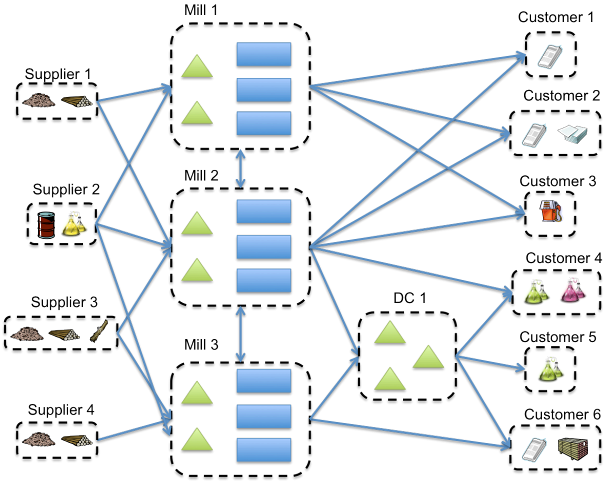

Figure 1. Biorefinery Supply Chain

The general supply chain problem addressed in this article is depicted in figure 1. Several biomass and other raw materials suppliers/locations supply the company's mills. These mills in turn transform raw materials into intermediate and final products, which can be transported to other mills, distribution centers and/or final customers according to their demand. Inventory of materials can be held in the company's facilities. Some customers and suppliers have contract agreements with the forest biorefinery company. For these, specific quantities of material must be obligatory purchased/sold every time period. For other spot customers and suppliers, demand/procurement can be partially fulfilled. Capacitated transportation routes link suppliers, facilities and customers together.

Inside a mill, capacitated processes transform raw materials and/or intermediates into various products. Some processes are fully dedicated while others are able to produce several products through different recipes. As well, boilers and turbines use fossil fuel and/or biomass to provide steam and electricity to the biorefinery. Process lines may use different recipes for manufacturing more than one product during a time period or bee idled. Changing recipes incurs transition time and costs. Moreover, processes can be shutdown for scheduled maintenance.

Mathematical Formulation

The model representing the supply chain presented above is formulated as a mixed integer linear programming problem with a discrete time horizon of 12

Nomenclature

Indices, index sets

$j \in J$	Supplier locations
$l \in L$	Mill locations
$k \in K$	Sales locations
$p \in P$	Processes
$r \in R$	Recipes
$m \in M$	Materials
$t \in T$	Time

Subsets

L_{jl}^{JL}	Suppliers that can supply mill
$L_{ll'}^{LL}$	Mills that can supply each other
L_{lk}^{LK}	Customers that can be served by mill
P_{lp}^{L}	Processes at mill
R_{lpr}^{P}	Recipes available on process
M_{jm}^{J}	Materials offered by suppliers
M_{lm}^{L}	Materials that are produced/processed at mill
M_{km}^{K}	Materials requested by customers
M_{lprm}^{R-in}	Input materials of a recipe
M_{lprm}^{R-out}	Output materials of a recipe
M_{jlm}^{JL}	Materials that can be transported between a supplier and a mill
$M_{ll'm}^{LL}$	Materials that can be transported between two mills
M_{lkm}^{LK}	Materials that can be transported between a mill and a customer

Parameters

a_{lprm}^{in}	Input factor of material m using recipe r on process p in mill l (throughput dependent)
a_{lprm}^{out}	Output factor of material m when using recipe r on process p in mill l
A_{lp}^{R}	Max. number of campaigns on process p in mill l
b_{lprm}^{in}	Input factor of material m when using recipe r on process p in mill l (time dependent)
b_{lpr}^{v-in}, b_{lpr}^{v-out}	Steam consumption / production factors for recipe r in process p in mill l
b_{lpr}^{w-in}, b_{lpr}^{w-out}	Electricity consumption / production factors for recipe r in process p in mill l
$c_{lpr}^{P-\mathrm{var}}$	Variable operating cost of using recipe r on process p in mill l (throughput dependent)
$c_{lpr}^{R-\mathrm{var}}$	Variable operating cost of using recipe r on process p in mill l (time dependent)
c_{lt}^{fix}	Fixed operating cost at facility l during time period t
c_{jlm}^{J-tr}	Transportation cost of material m from supplier j to mill l
$c_{ll'm}^{L-tr}$	Transportation cost of material m from mill l to mill l’
c_{lkm}^{K-tr}	Transportation cost of material m from mill l to customer k
c_{lm}^{M}	Storage cost of material m in mill l
c_{lp}^{sh}	Shutdown cost of process p in mill l
c_{lp}^{ch}	Transition cost on process p in mill l
c_{lt}^{w}	Electricity cost / selling price at mill l during time period t
c_{kmt}^{K}	Selling price of material m to customer k during time period t
c_{jmt}^{J}	Purchasing price of product m from supplier j during time period t
c_{kmt}^{K-s}	Sales cost for sending material m to customer k at during time period t
c_{lt}^{v}	Selling price of steam at location l during time period t
H_{lp}^{ch}	Transition time on process p in mill l
H_{lpr}^{R}	Minimum campaign length for recipe r on process p in mill l
H_{t}^{P}	Number of hours during time period t
$\underline{Q}_{lpr}^{R}$, $\overline{Q}_{lpr}^{R}$	Minimum and maximum throughput of recipe r on process p in mill l
$\underline{Q}_{lm}^{M}$, $\overline{Q}_{lm}^{M}$	Minimum and maximum storage quantity of material m in mill l
$\underline{Q}_{jmt}^{J}$, $\overline{Q}_{jmt}^{J}$	Min. and max. quantity of material m offered by supplier j during time period t
$\underline{Q}_{kmt}^{K}$, $\overline{Q}_{kmt}^{K}$	Min. and max. quantity of material m requested by customer k during time period t
$\underline{Q}_{lt}^{v}$, $\overline{Q}_{lt}^{v}$	Min. and max. steam quantity requested by local customers during time period t
$\overline{Q}_{jlm}^{J-tr}$	Maximum transportation quantity of material m between supplier j and mill l
$\overline{Q}_{ll'm}^{L-tr}$	Maximum transportation quantity of material m between mills l and l’
$\overline{Q}_{lkm}^{K-tr}$	Maximum transportation quantity of material m between customer k and mill l
s_{lm}^{start}	Inventory of material m at mill l at time 0
s_{lm}^{end}	Min. inventory of material m in mill l at time T
ε_{lpt}^{P}	Number of scheduled shutdown hours on process p in mill l during time period t

Variables

f_{jlmt}^{J}	Flow of material m from suppliers j to mill l during time period t
$f_{ll'mt}^{L}$	Flow of material m from mill l to mill l’ during time period t
f_{lkmt}^{K}	Flow of material m from mill l to customer k during time period t
h_{lprt}^{R}	Number of hours spent on recipe r on process p in mill l during time period t
s_{lmt}^{M}	Inventory of material m in mill l during time period t
v_{lt}^{L}	Quantity of steam sold in mill l during time period t
w_{lpt}^{in}, w_{lpt}^{out}	Input and output electricity quantity on process p in mill l during time period t
x_{lpmrt}^{R}	Input quantity of material m using recipe r on process p in mill l during time period t
y_{lprmt}^{R}	Output quantity of material m using recipe r on process p in mill l during time period t
y_{lprt}^{R-tot}	Total mass output of recipe r on process p in mill l during time period t
α_{lprt}^{R}	Selection of recipe r on process p in mill l during time period t (binary)
β_{lpt}^{R}	Transition between two consecutive time period t (binary)

months. Demand and procurement policies are elaborated at the tactical level. Yet, to represent more precisely the production processes and trade-offs between different manufacturing options, each time period is broken down into hours. The model has however limited scheduling considerations. It determines the number of hours and the throughput of processes for each recipe used, but will not give indications as per when to produce during the month.

As numerous combinations are in fact limited (e.g. processes being able to transform/produce only certain materials), several subsets have been created. Careful definition of sets and subsets will enable to solve the model only for feasible instances, thus reducing the size of the problem to be solved.

Objective Function

The objective of the model is to maximize the global net profit of the enterprise. The three first terms of the objective function represent revenues from sales of products, electricity and steam, respectively. Electricity sales/purchases are function of the production /consumption at the mill. Variable sales costs consist of duty, currency exchange, etc., which are customer specific. Transportation cost is calculated for each source to sink combination. Variable operating costs consist of two elements: costs that are a function of process throughput and others linked to operating time. Storage cost per month is considered for each material. A non-sequence dependent changeover cost is considered for each transition. The shutdown cost of a process is function of the number of scheduled maintenance hours during a time period. Procurement costs are equal to the flow of materials transported from each supplier to different facilities multiplied by the selling price. Finally, fixed costs are subtracted from the equation.

$$\max Profit =$$

$$\left(\begin{aligned}
&\sum_{t\in T}\sum_{\{l,k,m\}\in M^{LK}_{lkm}} f^{K}_{lkmt}\cdot c^{K}_{kmt} + \sum_{t\in T}\sum_{\{l,p\}\in P^{L}_{lp}} \left(w^{out}_{lpt} - w^{in}_{lpt}\right)\cdot c^{w}_{lt}\\
&+\sum_{t\in T}\sum_{\{l,p\}\in P^{L}_{lp}} v^{L}_{lt}\cdot c^{v}_{lt} - \sum_{t\in T}\sum_{\{l,k,m\}\in M^{LK}_{lkm}} f^{K}_{lkmt}\cdot c^{K-s}_{kmt}\\
&-\sum_{t\in T}\sum_{\{j,l,m\}\in M^{JL}_{jlm}} f^{J}_{jlmt}\cdot c^{J-tr}_{jlm} - \sum_{t\in T}\sum_{\{l,l',m\}\in M^{LL}_{ll'm}} f^{L}_{ll'mt}\cdot c^{L-tr}_{ll'm}\\
&-\sum_{t\in T}\sum_{\{l,k,m\}\in M^{LK}_{lkm}} f^{K}_{lkmt}\cdot c^{K-tr}_{lkm} - \sum_{t\in T}\sum_{\{l,p,r\}\in R^{P}_{lpr}} y^{R-tot}_{lprt}\cdot c^{P-\mathrm{var}}_{lpr}\\
&-\sum_{t\in T}\sum_{\{l,p,r\}\in R^{P}_{lpr}} h^{R}_{lprt}\cdot c^{R-\mathrm{var}}_{lpr} - \sum_{t\in T}\sum_{\{l,m\}\in M^{L}_{lm}} s^{M}_{lmt}\cdot c^{M}_{lm}\\
&-\sum_{t\in T}\sum_{\{l,p\}\in P^{L}_{lp}} c^{ch}_{lp}\cdot\left(\beta^{R}_{lp} + \sum_{\{l,p,r\}\in R^{P}_{lpr}} \alpha^{R}_{lprt} - 1\right)\\
&-\sum_{t\in T}\sum_{\{l,p\}\in P^{L}_{lp}} \varepsilon^{P}_{lpt}\cdot c^{sh}_{lp} - \sum_{t\in T}\sum_{\{j,l,m\}\in M^{JL}_{jlm}} f^{J}_{jlmt}\cdot c^{J}_{jmt} - \sum_{t\in T}\sum_{l\in L} c^{fix}_{lt}
\end{aligned}\right) \tag{1}$$

Model Constraints

Customer demand can be satisfied from different facilities. Customers and suppliers may request/offer materials between minimum and maximum bounds.

$$\underline{Q}^{K}_{kmt} \le \sum_{\{l,k,m\}\in M^{LK}_{lkm}} f^{K}_{lkmt} \le \overline{Q}^{K}_{kmt} \quad \forall\{k,m\}\in M^{K}_{km}, t\in T \tag{2}$$

$$\underline{Q}^{J}_{jmt} \le \sum_{\{j,l,m\}\in M^{JL}_{jlm}} f^{J}_{jlmt} \le \overline{Q}^{J}_{jmt} \quad \forall\{j,m\}\in M^{J}_{jm}, t\in T \tag{3}$$

This simple formulation of supply and demand allows to model different supplier/customer types and thus to segment them. Contract customers can be modeled by setting minimum and maximum boundaries to the same value, thus forcing the demand to be met. Spot demand can be modeled by setting the minimum boundary to 0, allowing any demand fulfillment level. Equations (4-5-6) limit the amount of materials that can be transported between locations. The material balance at a facility is equal to the previous inventory, plus/minus material incoming from and outgoing to other sites, as well as the consumption/production from processes (Eq. 7). For time t=1, this equation needs to be slightly modified by replacing variable s^{M}_{lmt-1} with an initial storage parameter s^{start}_{lm}. Equation (8) ensures that the optimization model does not completely deplete the inventory at the end of the planning horizon. Each site has storage capacity constraints, as shown in Eq. (9). One special attribute of the formulation is the modeling of distribution centers. As distribution centers are facilities where materials are stored but not transformed, these can be modeled as facilities for which there are no processes, the subset P^{L}_{lp} being empty for this *l*. Hence, equations (10-21) become non-relevant and only equations related to procurement, inventory, transportation and demand are active.

$$f^{J}_{jlmt} \le \overline{Q}^{J-tr}_{jlm} \quad \forall\{j,l,m\}\in M^{JL}_{jlm}, t\in T \tag{4}$$

$$f^{L}_{ll'mt} \le \overline{Q}^{L-tr}_{ll'm} \quad \forall\{l,l',m\}\in M^{LL}_{ll'm}, t\in T \tag{5}$$

$$f^{K}_{lkmt} \le \overline{Q}^{K-tr}_{lkm} \quad \forall\{l,k,m\}\in M^{LK}_{lkm}, t\in T \tag{6}$$

$$\begin{aligned}
s^{M}_{lmt} &= s^{M}_{lmt-1} + \sum_{\{j,l,m\}\in M^{JL}_{jlm}} f^{J}_{jlmt} - \sum_{\{l,k,m\}\in M^{LK}_{lkm}} f^{K}_{lkmt}\\
&+ \sum_{\{l,l',m\}\in M^{LL}_{ll'm}} f^{L}_{l'lmt} - \sum_{\{l,l',m\}\in M^{LL}_{ll'm}} f^{L}_{ll'mt} + \sum_{\{l,p,r,m\}\in M^{R-out}_{lprm}} y^{R}_{lprmt}\\
&- \sum_{\{l,p,r,m\}\in M^{R-in}_{lprm}} x^{R}_{lprmt} \quad \forall\{l,m\}\in M^{L}_{lm}, t\in T, t>1
\end{aligned} \tag{7}$$

$$s^{M}_{lmT} \ge s^{end}_{lm}, \quad \forall\{l,m\}\in M^{L}_{lm}, t=T \tag{8}$$

$$\underline{Q}^{M}_{lm} \le s^{M}_{lmt} \le \overline{Q}^{M}_{lm} \quad \forall\{l,m\}\in M^{L}_{lm}, t\in T \tag{9}$$

Each process has an offline/idle recipe that can be selected for when the process is not needed. Like other recipes, there is a variable cost (per hour) associated to it that allows the consideration of process idling costs. Equation (10) demands that at least one recipe (campaign) is selected during one time period Transitions can occur during one or between two consecutive time periods. To ensure the latter, Eq. (11) triggers a transition variable if two different recipes are used between time periods. It is to be noted that in certain instances where several different recipes are selected during time periods, this formulation can overestimate the number of transitions by one. However, this overestimation can be viewed as an operational penalty for changing recipes too often. A planner typically follows some heuristics to ensure that operational issues don't arise. For instance, he can assign a maximum number of campaigns allowed per time period in order to limit the number of changeovers (Eq. 12). To further limit the number of changeovers, he can specify minimum and maximum campaign lengths, as shown in Eq. (13). Processes must be permanently utilized (or idled) during a time period. Equation (14) stipulates that the available processing hours equals the number of hours during a time period minus scheduled maintenance shutdown and lost time during transitions. Each recipe has minimum and maximum throughput boundaries (tons/hour), as shown in Eq. (15).

$$\sum_{\{l,p,r\}\in R^{P}_{lpr}} \alpha^{R}_{lprt} \geq 1 \quad \forall\{l,p\}\in P^{L}_{lp}, t\in T \tag{10}$$

$$\alpha^{R}_{lprt} + \alpha^{R}_{lpr't-1} - 1 \leq \beta^{R}_{lpt} \quad \forall\{l,p,r\},\{l,p,r'\}\in R^{P}_{lpr}, t\in T, r\neq r', t>1 \tag{11}$$

$$\sum_{\{l,p,r\}\in R^{P}_{lpr}} \alpha^{R}_{lprt} \leq A^{R}_{lp} \quad \forall\{l,p\}\in P^{L}_{lp}, t\in T \tag{12}$$

$$\alpha^{R}_{lprt}\cdot H^{R}_{lpr} \leq h^{R}_{lprt} \leq \alpha^{R}_{lprt}\cdot\left(H^{P}_{t} - \varepsilon^{P}_{lpt}\right) \quad \forall\{l,p,r\}\in R^{P}_{lpr}, t\in T \tag{13}$$

$$\sum_{\{l,p,r\}\in R^{P}_{lpr}} h^{R}_{lprt} = H^{P}_{t} - \varepsilon^{P}_{lpt} - \left(\beta^{R}_{lpt} + \sum_{\{l,p,r\}\in R^{P}_{lpr}} \alpha^{R}_{lprt} - 1\right) H^{ch}_{lp} \quad \forall\{l,p\}\in P^{L}_{lp}, t\in T \tag{14}$$

$$h^{R}_{lprt}\cdot \underline{Q}^{R}_{lpr} \leq y^{R-tot}_{lprt} \leq h^{R}_{lprt}\cdot \overline{Q}^{R}_{lpr} \quad \forall\{l,p,r\}\in R^{P}_{lpr}, t\in T \tag{15}$$

Equation (16) links the material conversion from feedstock to products. Linear recipes functions are used to represent process where raw material consumption depends on the utilization rate of the equipment employed, as introduced by (Kannegiesser, 2008). Equation (17) relates the material output to the total output of a process. Processes require or produce steam and/or electricity for their operation. Equations (18-19) calculate electricity consumption/ production of processes based on the recipe used. The steam balance must also be satisfied in each mill (Eq. 20). Enough steam must be produced by boilers and other steam producing equipments to satisfy the needs of other steam consuming processes. If local steam consumers (e.g. district heating or eco-parks) exist near the mill, extra steam may be sold according to their requested minimum and maximum demand (Eq. 21). Otherwise, it may be vented off if not necessary.

$$x^{R}_{lprmt} = \sum_{\{l,p,r,m\}\in M^{R-in}_{lprm}} \left(y^{R-tot}_{lprt}\cdot a^{in}_{lprm} + h^{R}_{lprt}\cdot b^{in}_{lprm} \right) \quad \forall\{l,p,r,m\}\in M^{R-in}_{lprm}, t\in T \tag{16}$$

$$y^{R}_{lprmt} = y^{R-tot}_{lprt}\cdot a^{out}_{lprm} \quad \forall\{l,p,r,m\}\in M^{R-out}_{lprm}, t\in T \tag{17}$$

$$w^{in}_{lpt} = \sum_{\{l,p,r\}\in R^{P}_{lpr}} y^{R-tot}_{lprt}\cdot b^{w-in}_{lpr} \quad \forall\{l,p\}\in P^{L}_{lp}, t\in T \tag{18}$$

$$w^{out}_{lpt} = \sum_{\{l,p,r\}\in R^{P}_{lpr}} y^{R-tot}_{lprt}\cdot b^{w-out}_{lpr} \quad \forall\{l,p\}\in P^{L}_{lp}, t\in T \tag{19}$$

$$\sum_{\{l,p,r\}\in R^{P}_{lpr}} y^{R-tot}_{lprt}\cdot b^{v-out}_{lpr} \geq \sum_{\{l,p,r\}\in R^{P}_{lpr}} y^{R-tot}_{lprt}\cdot b^{v-in}_{lpr} + v^{L}_{lt} \quad \forall l\in L, t\in T \tag{20}$$

$$\underline{Q}^{v}_{lt} \leq v^{L}_{lt} \leq \overline{Q}^{v}_{lt} \quad \forall l\in L, t\in T \tag{21}$$

Test Case Results and Discussion

The mathematical formulation presented above has been tested using real data from a Canadian forestry company. The SC modeled in this test case consists of 3 mills, 1 distribution center, 47 suppliers, 29 customer clusters, 58 materials, 51 processes and 158 recipes, for a total of 26017 variables including 1896 binary, and 43291 constraints. This model has been implemented in IBM ILOG CPLEX Studio IDE 12.2 on an Intel Macbook Pro with 2.4 GHz and 2 Go RAM. Solutions with a 0,1% relative optimality gap have been obtained in about 30 seconds. The test case shows that this mathematical formulation can be used easily for testing quickly different scenarios, as results are obtained in an acceptable time even for an industrial application. Hence, important elements of decision-making related to the supply chain of future biorefineries can be evaluated.

Biorefinery Design

The design and the level of manufacturing flexibility needed to mitigate the risk of market volatility can be determined using (Mansoornejad et al., 2010) hierarchical design procedure. For this, various design alternatives and their integration in an existing mill are first elaborated for certain product/process portfolios. Some of these alternatives have a higher level of process flexibility than others, being able to produce different products under different rates or to use different raw materials. The SC model is then run for each of the design alternatives under various market scenarios to identify which ones perform the best and the least under market volatility. Non-robust alternatives can then be screened out, and the remaining ones can be compared under return on investment criteria.

Once the decision maker selected the preferred product/process design alternatives, he can evaluate the performance of different supply chain network options under market volatility. The idea for this step follows the previous one. He identifies several SC networks, represents them in the tactical model and tests them under different market scenarios to identify the best ones.

Biorefinery Supply Chain Management

Considering that sustainable alternatives can be screened through the methodology described before, other important issues about management of the new biorefinery SC should be considered by the stakeholders of the company. Sound strategic level decisions are crucial for ensuring the long-term profitability, but it's at the tactical-operational level that profit and cash flow are generated. In that sense, new SC policies might have to be developed to adapt the biorefinery to different market environments in order to operate in a margins-based fashion. A model like the one presented in this paper can be used to help defining such policies. Assuming that biorefineries will have a certain level of flexibility in regards to the volume and types of products that are manufactured, the model would optimize key SC decisions to be made under different market scenarios, such as the amount of each product to produce in a time period (production throughput), the way these products are manufactured (recipe selection) and the level of spot vs. contracts sales.

Contracts are good for securing a certain level of production and sales, which is a prerequisite in the process industry because of the capital intensiveness. On the other hand, allocating all or most sales under contracts hinders opportunities for more profitable contracts or spot sales. Especially, as spot sales do not stipulate long-term agreements and do not necessarily need to be fulfilled, active decisions related to the acceptance or rejection of spot bids can be made. Hence, the decision of allocating a certain percentage of the capacity to contract sales in order to secure the market and yet to keep some capacity flexibility for taking advantage of favourable spot market price can play a crucial role in the firm's profitability (Feng et al., 2008). However, in the case of some flexible biorefineries, where several process routes can be used for a fixed amount of raw material input, the problem might be reversed. Some processing options might be designed with an overcapacity to provide robustness in market volatile conditions, i.e. to give the flexibility of selling the most profitable products in greater quantities. In this situation, decisions regarding contract and spot sales allocation must still be made, but perhaps with more spot sales flexibility.

Decisions regarding product throughput and recipe selection, i.e. manufacturing flexibility parameters, have a direct incidence on demand fulfillment, but also on procurement through raw materials utilization and on energy consumption, two of the most important variable cost components in forest biorefineries. In margins-based operations, a planner would have to choose upon several manufacturing flexibility parameters to maximize profit. More costly options and idling may even be better in certain cases. For example, a process recipe using one type of biomass may have a better yield and consume less energy than another one using cheaper biomass. In this case, it is not obvious to assess which recipe provides the best margins. It is therefore important evaluate costs using a bottom-up approach for better representing the trade-offs between ways of production.

These management issues highlight the fact that true margins cannot be assessed without considering simultaneously procurement to sales in an integrated framework. Margins-based SC policies for different market scenarios cannot be elaborated in isolation of other departments of a company.

Conclusions

In this paper, an integrated tactical planning model for the forest biorefinery has been presented. The model formulation is flexible enough to represent different product/process portfolios, levels of manufacturing flexibility and SC networks alternatives. Through the analysis of different market scenarios, the model can help in defining the best design alternative according to SC criteria. As well, it can be used to define margins-based SC policies to be followed under different market environments to achieve higher profitability. Future work includes a case study evaluation of a forestry company transforming to the biorefinery and the evaluation of SC policies for different market environment scenarios.

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