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Strategic Decision Analysis of Multi-product Biorefineries

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A decision support system is formulated for a multi-product biorefinery. A structured approach is used for feed, product, and technology selection and capacity design. Uncertainty in ethanol prices is modeled using real-options analysis. The results show prefernece for an incremental capacity design over economies of scale, and selection of a higher costing flexible production platform that can coproduce multiple products.

1. Introduction

Commercial biomass refineries require large upfront capital investments and are plagued by large product demand and price uncertainty. Consequently penetration into the renewables' industry is fraught with considerable risks; it is paramount for a fledgling enterprise to mitigate these market risks with a sound strategic capacity design plan and careful analysis of feed, product and technology selection decisions. The following paper introduces an optimization-based decision support system that enables emerging bio-enterprises to evaluate different portfolio configurations, and design a strategy for capacity expansion in the face of parameter uncertainties. The decision support system is represented in 3 steps (Figure 1). The 1st step is a screening model which provides a preliminary set of enterprise portfolio choices (feedstock, product, technology) to the 2nd step which evaluates model sensitivity to parameter variation. The 3rd step models uncertainty in the "sensitive parameters".

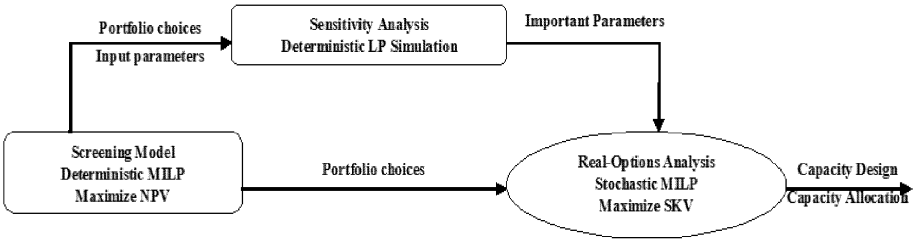

Figure 1: Decision support architecture for strategic planning and assessment of biorefineries

Following the real options analysis, the decision support system yields a strategic capacity design and portfolio plan that manages downside risks involved with large upfront capital investments and market uncertainties. Such a methodology, if correctly applied, can yield asymmetric returns towards the upside. This framework is applied to a fermentation-based flexible, multi-product biomass refinery in the following sections.

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2. Biorefinery Description

A sample biomass refinery was formulated in Figure 2. The potential product slate was derived from Lynd et al (2005). Like a petroleum refinery, the biomass refinery boasts of low margin fuels like ethanol and butanol coproduced with high margin chemicals like succinic and lactic acid; the same pretreatment and fermentation equipment can be used to produce a multitude of products, making possible switching output product volumes with changing market conditions. Furthermore, all the electricity used by the production processes is generated internally using biomass lignin separated from the pretreated feed stream. CO_2 produced during utility generation and fermentation is captured and either used as a raw material (succinic acid) or sequestered underground.

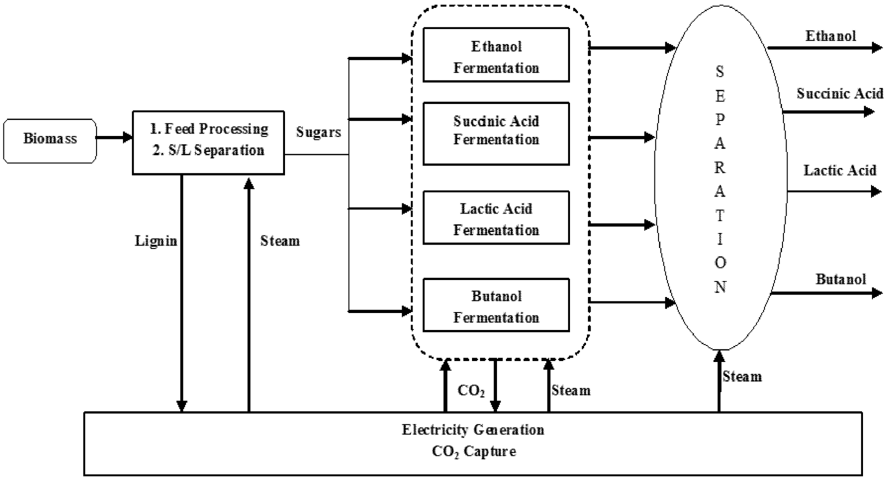


Figure 2: Prospective process flow diagram for integrated biorefinery

3. Model Formulation

A description of model constraints is provided for each optimization model.

3.1 Screening Model

The first step in the framework is a deterministic optimization MILP model which acts as a screening model that filters the most promising feed/technology/product sets, from an initial portfolio of available choices. This is done in order to reduce the computational burden of options optimization. The Net present value (NPV) of all future cash flows as a result of facility operation is maximized. It is assumed that ethanol or butanol have to be produced in order to coproduce any high value co-product (succinic or lactic acid). The enterprise can choose between a flexible technology platform that can coproduce and switch between many products, and an inflexible technology that can only produce a single product at a time. The flexible technology requires a higher capital investment and incurs higher operating costs. Other constraints imposed include material balances, and capacity and biomass availability.

3.2 Sensitivity Analysis

Once an optimal feed/product/technology set is selected, sensitivity analysis is conducted on the model in order to determine what parameters have the most profound effect on the NPV of the projects. Parameters are classified as endogenous or exogenous. Endogenous parameters can be controlled by enterprise and include capital and operating expenses. Exogenous parameters include product demand and prices, and feedstock availability and costs. Integer restrictions are removed from the model and it is assumed that all projects are constructed simultaneously. The resulting model is an LP which is solved in GAMS.

3.3 Real-Options Analysis

Real options analysis is a new paradigm in engineering that has been successfully applied to natural resource projects that have a high degree of uncertainty in product prices and demands along with large upfront capital investments and construction lead times. For a thorough discussion of this approach readers are referred to (Davis and Owens, 2003; Miller and Waller, 2003; Rogers et al., 2002). Stochastic parameter distributions are discretized using a non-recombinant binomial tree (Wang and De Neufville) and the results are represented using a decision tree. The time horizon for options optimization is 12.5 years with five 2.5-year time steps. Each time step can involve an up or a down move in the uncertain variable, representing a scenario, yielding a total of 16 scenarios. Environmental sustainability is modeled by mandating carbon capture and sequestration along with an integrated utility facility. In addition to previously mentioned constraints, budget, capital, and loan related constraints are also imposed. The model is termed the stakeholder value (SKV) model, where SKV is defined as the value of an enterprise not only to its shareholders but also to the surrounding community and environment. Our formulation uses a free cash flow to firm (FCFF) framework (Damodaran) with added mitigation costs and credits (Eq. 1) to yield the SKV (Eq. 2). The expected SKV is calculated as the sum of the probability-weighted stakeholder values over all scenario realizations (Eq. 3).

$$\mathrm{FCFF}_t = \mathrm{R}_t - \mathrm{Opex}_t - \mathrm{Taxes}_t + \mathrm{Credits}_t - \mathrm{Capex}_t - \Delta\mathrm{Inv}_t \tag{1}$$

$$\mathrm{SKV} = \sum_t \frac{\mathrm{FCFF}_t}{(1+r)^t} + \mathrm{SV} \tag{2}$$

$$\mathrm{E}[\mathrm{SKV}] = \sum_s p(s) \cdot \mathrm{SKV}_s \tag{3}$$

where, R_t is the revenue, $Opex_t$ and $Capex_t$ are the operating and capital costs, and ΔInv_t is the change in the inventory value. SV is the continuing value of the enterprise beyond the time horizon, while r is the weighted average cost of capital.

4. Model Parameters

This section describes only those parameters that are relevant to the results. Corn stover, wheat straw and bagasse were used as proxies to describe the potential feedstock choices; the delivered costs ($/t) and corresponding ethanol yields (L/kg) to product were assumed to be {32, 30, 37} and {340, 330, 355}. Each feedstock was assumed to have different availabilities and spoilage rates during storage. Butanol and co-product related parameters were derived from Lynd et al (2005) and were assumed equal for each biomass source. Economies of scale were represented assuming the enterprise can select any one of the three available capacity increments (1000 t/year) represented by {18, 9, 4.5} corresponding to a fixed capital investment (FCI) ($M) represented by {98, 60, 40}. The variable capital investment (VCI) was divided into processing equipment costs, considered equal for all products (0.078 $/kg biomass), and product separation equipment costs (Lynd et al, 2005). A construction delay of 2.5 y is assumed. CO_2 mitigation expenses were assumed to $10/t for fermentation gas, and 50 $/t for utilities. Mitigation credits were set at 30 $/t. Two different options were considered; Growth options (Wang and De Neufville, 2004) for timing of capacity expansion and switching options (Bollen, 1999) for allocating capacity between products.

5. Results and Discussion

The results yielded by the models are discussed in the following subsections.

5.1 Screening Model

Wheat straw was selected as the feedstock. Interestingly, wheat straw has a lower product yield, delivered cost and availability. This indicates that marginal product yield improvement may not always warrant a more expensive feedstock. Despite higher capital and operating costs, the flexible production platform was chosen over the single-product (inflexible) production platform. Finally ethanol was chosen as the base biofuel while both succinic and lactic acid were selected as value added chemicals.

5.2 Sensitivity Analysis

Based on the selected feed/product/technology set, sensitivity analysis was conducted for feedstock costs and availability, FCI and VCI, operating costs, and product demand and prices. These parameters were varied between ± 50 % independently from the base case, and the resultant LP was solved for each variation. The results are represented in the form of tornado diagrams in Figure 3.

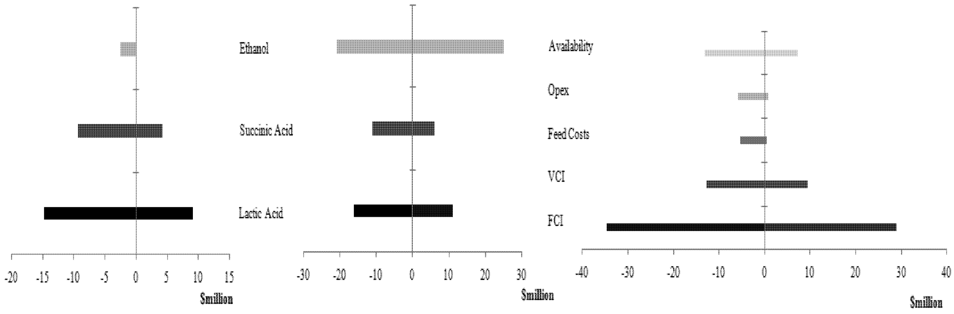


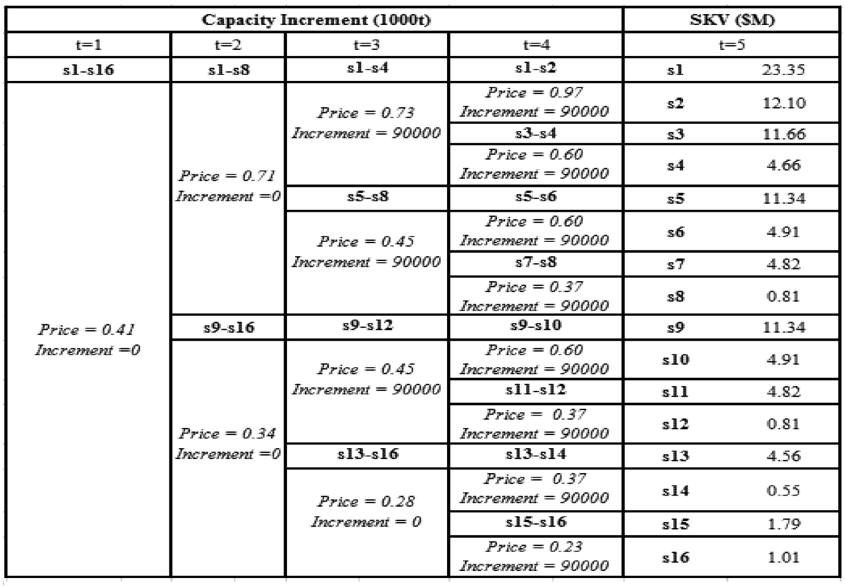
Figure 3: Tornado diagram (from left to right): demand, prices, other parameters

As evidenced from the diagram, the most important parameters that affect NPV of the projects include lactic acid demand, ethanol prices, and total capital investment. Of these, capital investment is an endogenous parameter that is market diversifiable. Stochastic modeling of all exogenous parameters can increase computational complexity exponentially. Hence we model the exogenous parameter that has the biggest effect on the NPV, ethanol prices. The ethanol prices are assumed to follow a normal distribution, with a mean of 0.41 $/gal and a standard deviation of 15 %. The stochastic prices are discretized to a binomial distribution with a drift parameter of 2 %.

5.3 Real Options Analysis

The overall expected SKV was calculated to be $7.5M. Investigating Table 1, we can state that if the prescribed plan is followed for the given ethanol price process, the enterprise has a maximum upside of $23 M (Scenario 1), and a downside of $550,000 (Scenario 14). There is a 20 % difference between the stochastic and deterministic cases, where ethanol prices were calculated as the weighted sum of the stochastic scenarios. Capacity is not incremented until the 3rd time period implying that a minimum price of 0.45 $/gal is necessary to warrant capital investment. Capacity is incremented for all price scenarios during the 4th time period indicating reduced downside risks. Interestingly, capacity is not incremented at t=2 (Scenarios 1-8), when ethanol prices are 0.55 $/gal, higher than the minimum ethanol price at t=3. This is where the utility of the real-options framework is evident; the downside risk of the price process is much higher at t=2, hence warranting a “wait-and-see” approach. Once some of the price uncertainty reveals itself at t=3, and some of the downside risks are mitigated, the enterprise can maximize the upside potential of ethanol price movements by initiating facility construction. There is an 8 % difference in the SKV when the optimizer is forced to start facility construction during the 2nd time period.

Table 1: Exercise of growth options. Note: Prices are in $/L



Capacity Increment (1000t)				SKV ($M)	
t=1	t=2	t=3	t=4	t=5	
s1-s16	**s1-s8**	**s1-s4**	**s1-s2**	**s1**	23.35
Price = 0.41 *Increment =0*	*Price = 0.71* *Increment =0*	*Price = 0.73* *Increment = 90000*	*Price = 0.97* *Increment = 90000*	**s2**	12.10
			s3-s4	**s3**	11.66
			Price = 0.60 *Increment = 90000*	**s4**	4.66
		s5-s8	**s5-s6**	**s5**	11.34
		Price = 0.45 *Increment = 90000*	*Price = 0.60* *Increment = 90000*	**s6**	4.91
			s7-s8	**s7**	4.82
			Price = 0.37 *Increment = 90000*	**s8**	0.81
	s9-s16	**s9-s12**	**s9-s10**	**s9**	11.34
	Price = 0.34 *Increment =0*	*Price = 0.45* *Increment = 90000*	*Price = 0.60* *Increment = 90000*	**s10**	4.91
			s11-s12	**s11**	4.82
			Price = 0.37 *Increment = 90000*	**s12**	0.81
		s13-s16	**s13-s14**	**s13**	4.56
		Price = 0.28 *Increment = 0*	*Price = 0.37* *Increment = 90000*	**s14**	0.55
			s15-s16	**s15**	1.79
			Price = 0.23 *Increment = 90000*	**s16**	1.01

Switching options were also recognized by the formulation. 19555 t of biomass processing capacity that was initially allocated to Lactic acid production was switched over to ethanol production in the final time period for Scenarios 5 through 14, while for

Scenarios 1 through 4, 11300 t of biomass capacity was re-allocated from succinic acid production to ethanol production. There was no capacity switching for Scenarios 15 and 16. This is prescribed despite prevalent switching costs, fixed costs associated with idle equipment capacity. The result demonstrates the utility of designing for production flexibility in a biorefinery; while initially larger portions of processing capacity are dedicated to co-product generation, as ethanol prices become more favorable capacity can be reallocated in order to increase ethanol production and drive profits higher.

6. Conclusions

A structured approach was used to determine the portfolio design and an incremental capacity plan for a biorefinery in the face of stochastic inputs and outputs. The methodology discussed was tested on a multi-product flexible biorefinery with a product slate of ethanol, succinic acid, and lactic acid. Despite substantial economies of scale, our approach was able to demonstrate that smaller capacity increments may be more ideal if faced with large uncertainties in revenue streams. Growth and switching options were modeled for using a stochastic MILP model, and both options were exercise over the time horizon. Growth options were exercised to mitigate risks associated with ethanol price uncertainty, while switching options were exercised to take advantage of favorable swings in ethanol prices.

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