Metrics for Evaluating the Forest Biorefinery Supply Chain Performance

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Abstract
The forest biorefinery (FBR) is emerging as a possibility for improving the business model of forest product companies, however introduces significant challenges in terms of market, technological, and financial risks - which can be addressed to an important extent in the design of supply chains (SC). For sustainable decision-making regarding biorefinery strategies, criteria from different perspectives, i.e. economic, environmental and social, should be considered. The economic criteria that are used for decision making typically do not consider volatility, whereas today's market is subject to volatilities in terms of price and demand. It is critical that biorefinery strategies are flexible in order to be robust to market volatility. This paper presents metrics of flexibility and robustness, showing the performance of the SC in a dynamic environment. These metrics are suitable to be used in a multi-criteria decision-making (MCDM) framework for the evaluation of the FBR SC strategies. Moreover, a “conditional value-at-risk” parameter is introduced for analyzing levels of risks in making market-related decisions.

Keywords: Forest Biorefinery, Supply Chain, Flexibility, Robustness, Value-at-risk

1. Introduction
FBR is increasingly considered as a possibility for improving the forest products company business model, though it poses market, technological, and financial challenges. Thus, potential FBR implementation strategies must be analyzed using different perspectives to identify the most promising ones [1]. Sustainable development includes three dimensions; economic, environmental, and social. MCDM frameworks can consider several metrics provided from different analysis tools to permit the analysis of different strategies [2]. Hence, MCDMs can be used for sustainability analysis, if appropriate metrics for economic, environmental and social aspects of a strategy can be assessed.

Economic metrics that are used in decision making, which are mainly related to the profitability of a strategy, are incapable of accounting for the market volatility [3]. Sensitivity analysis is typically executed to address the impact of possible market scenarios on profitability. Even in this case, the problem is viewed as a steady-state case and the dynamism of the market, i.e. changes in price and demand over the given time period, are ignored. Moreover, it is not easy to use the result of a sensitivity analysis in an MCDM framework. Instead, it is desirable to reflect the response of a strategy to such dynamism by relevant metrics. This paper presents metrics of flexibility and robustness that can be used in an MCDM framework, in conjunction with economic
criteria, for the evaluation of the FBR SC strategies. These metrics are the outcomes of an analysis that evaluates the impacts of the SC design on operational SC activities.

2. Problem statement

The decisions as to which products to produce, which technologies to employ, with which companies to make partnerships, and which parts of the SC to redesign are major strategic decisions addressed by a forest product company implementing the FBR. The SC of an FBR must be designed to be flexible, so that it can have a robust response to market volatility. The goal of this paper is to evaluate the performance of several FBR design options using metrics of flexibility and robustness. Design options with different levels of flexibility in production and with different SC networks are considered, and their performance in case of several market scenarios is tested. An SC optimization model calculates the profit of design options for every market scenario and quantifies the flexibility and robustness of each option using the introduced metrics. These metrics can be further used in an MCDM framework along with metrics provided by other tools, e.g. life cycle analysis (LCA), to identify the best option. Finally, a conditional value-at-risk parameter is introduced to analyze levels of risk in making market-related decisions and to provide required information for profit-risk trade-offs.

3. Performance metrics

3.1. Manufacturing flexibility: Metric of flexibility (MF)

Today’s market is subject to huge volatilities in terms of price and demand. An FBR will be exposed to this kind of volatile environment and hence, flexibility, of any possible type, must be exploited in an FBR to mitigate risks. An FBR will be able to produce several products, including P&P products, bioproducts, and energy. Producing several products implies the opportunity to take advantage of manufacturing flexibility, i.e., producing different products (product flexibility) at different volumes (volume flexibility) in different time periods. In a volatile market, depending on feedstock and product prices as well as supply and demand, manufacturing flexibility can be exploited, and the mill can produce different products in different amounts to optimize the profit. To quantify the volume flexibility, MF shown in equation 1, inspired by [4], is introduced:

\[
MF = \sum_t \sum_p \sum_m \left( \frac{C_{mpt} - C_{np}}{C_{np}} \right)
\]

where \(C_{mpt}\) is the amount of product \(m\) that is produced on process \(p\) in time period \(t\) and \(C_{np}\) is the amount of product \(m\) produced on process \(p\) by the nominal production rate over the same number of processing hours.

3.2. Robustness: Metric of robustness (MR)

In a robust design the control parameters of a system are selected in such a way that the desirable measured function do not diverge significantly from a given value [5]. Several robustness metrics have been introduced thus far [6]. Well-known metrics are standard deviation and mean absolute deviation. For the sake of simplicity and interpretability for an MCDM panel, we use a simple formulation as robustness metric, as shown in equation 2.

\[
MR = \left( \frac{\sum_{Sc} (Pr_{Sc} - Pr_B)}{Pr_B} \right)^{-1}
\]

where \(Pr_B\) is the base case profit, \(Pr_{Sc}\) is the profit for scenario \(Sc\) and \(N_{Sc}\) is the number of scenarios. To quantify the downside risk of volatility, scenario profits that are less than the base case profit are considered in this equation.
3.3. Conditional value-at-risk (CVAR)
As discussed by Verderame and Floudas [7], CVAR aims at guarding against realization of uncertain parameters by going beyond the expected evaluation when expressing the uncertainty of system parameters. A loss function must be defined as a function of decision vector and uncertain parameters with a probability distribution. Using the loss function and the acceptable loss level, two constraints are added to the optimization formulation which restrict the evaluation of the system’s variables according to a user-specified risk aversion parameter.

Inspired by [7], a constraint is added to the optimization formulation, in which the contractual order acceptance percentage (OA) should be bigger than a risk factor. A high OA implies less risk, because contractual orders are fixed in price and amount over the long term and thus they can secure the profit. On the other hand, lower OA connotes more spot orders which might cause profit increase, but poses higher risks, as spot demands are not certain. The added constraint is shown in equation 3:

\[
\frac{\text{Volume associated with the accepted contractual orders}}{\text{Volume associated with all contractual orders}} > \alpha \quad (3)
\]

where \(\alpha\) is the risk parameter. Probability of market scenarios has not been considered in this study.

3.4. SC optimization framework
The SC model aims at maximizing SC profit. Inspired by the tactical model developed for the chemical industry presented in [8], this model considers the management of a multi-product, multi-echelon SC, including production facilities, inventories and a number of customer zones. Feedstock is provided by several suppliers. Processes are either dedicated or flexible, i.e. they are able to produce several products through different recipes. Changing from one recipe to another incurs changeover cost and time. The steam required for each process is provided by both fuel and biomass. Inventories can receive material from different sources and plants, and supply different markets. Each market places demand in two ways: by contract, i.e., for the long term, and on the spot, i.e., for the short term. In case of a contract, specific quantities of products must be sold to the customer in specific time periods. The spot demand can be partially fulfilled. Transportation routes link suppliers, facilities and customers together. The model is formulated as an MILP with a discrete time horizon of 52 weeks. The model exploits the potential for flexibility and determines which orders must be fulfilled, how much of which products must be produced, stored, and delivered to the market.

4. Results and discussion
A simplified example, including two biorefinery design options, is presented, as shown in figure 1. In option B-1, there are two parallel lines, including a fermentor, which is flexible, and a recovery system. One line produces lactic acid (LA) and the other line is able to produce both succinic acid (SA) and malic acid (MA), as one recovery system can be used for both products. To increase the level of flexibility, a new SA/LA recovery system is added in option B-2 so that the first line can produce all three products. Based on the market conditions, the fermentor produces one of the products and the relevant recovery system is used, while the other recovery system will be out of operation. The SC optimization is run for nine market scenarios, and profit, flexibility and robustness metrics of each design is calculated.
Figure 1. Design options

Table 1 shows the calculated profit and flexibility of both options for each market scenario. The flexibility metric for the second option, which has more potential for flexibility, is higher for all scenarios. Profit is also higher for the more flexible option and that shows more flexibility results in more profit. Using average profit, a simple return on investment (ROI) was estimated, which shows the more flexible option has a higher ROI. Thus, although extra capital should be spent on more flexible option, this extra capital is well compensated by the increase in flexibility. Finally, robustness metric shows that the more flexible option is more robust against market volatility and the deviation of profits from the base case profit is less than that of the less flexible option. The results are shown graphically in figures 2 and 3.

Table 2 shows the result of CVAR studies for option B-1. SC model was run for eight market scenarios and the profit was calculated for several levels of OA. The maximum profit happens in different percentages (highlighted in yellow), showing that there is not one optimum percentage for all scenarios. In 80% OA, the average profit is the highest and the robustness metric is the lowest, except compared to the 100% OA which has a low profit, but the best robustness. Therefore, 80% OA can be chosen over lower OAs and compared to 100% OA. Decision makers with low risk tolerance may choose 100% OA which has better robustness, while those with higher risk tolerance can choose 80% OA which has the highest profit.

Table 2. Profit, robustness and average profit for option B-1

Figure 4 and 5 show the results graphically. For the optimistic scenarios (3 and 5), the maximum profit happens in lower OAs compared to other scenarios, because in these
scenarios the spot market is strong and more spot orders are accepted and lower OA results in higher profit. By contrast, for pessimistic scenarios (2 and 4), more contracts are accepted, because the spot market is weak. For the worst case scenario (8), the maximum profit is acquired at 100% OA, because the spot market is not profitable at all and at 100% OA, where all contracts are made, the profit is maximized.

![Percentage of Orders Accepted for Each Scenario Resulted in the Highest Profit](image1)

![Average Profit and Robustness vs. Contractual Order Acceptance Percentage](image2)

Figure 4. OA for spot and contractual orders  Figure 5. Profit and robustness vs. OA

5. Concluding remarks

To mitigate the risks of market volatility, the processes and the SC must be designed flexible to have a robust response to changing market. Although more flexible design alternatives are more capital intensive, the results show that this capital will be very well paid off by increasing the capability of the system to react properly to market changes and a more flexible alternative will be more profitable and robust. Moreover, the CVAR studies show that optimum OA is different for each market scenario. This study demonstrates that lower risks may imply lower profit and thus, an appropriate trade-off analysis ought to be performed to choose the right OA.

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References