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Scenario-based strategic supply chain design and analysis for the forest biorefinery using an operational supply chain model

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ABSTRACT

Supply chain (SC) design involves decisions for the long term, e.g. determining products, process technologies, number, location and capacity of different SC nodes, production rates, as well as suppliers, markets and partners. The forest biorefinery (FBR) is emerging as a new possibility for improving forestry companies' business models, however introduces significant technological, economic and financial challenges—which can be systematically addressed in strategic SC design. In order to reduce the burden of such challenges, partnership with companies whose expertise brings value and experience to the forestry companies' new business model is essential for FBR implementation. In this regard, redesigning the forestry SC in order for it to be aligned and consistent with the partner's SC, and in other words, designing a new integrated SC is of crucial importance.

This paper presents a scenario-based approach to strategic SC design for the FBR, designing the SC based on the impacts of the design on operational SC activities. Two kinds of scenarios are used; market scenarios representing market volatility and SC network scenarios (referred to as alternatives) representing different biorefinery options/strategies. In order to analyze the impacts of SC alternatives on operational activities, a tactical/operational SC model examines the advantages and disadvantages of each alternative by exploiting the capability of the SC for flexibility in the case of the market scenario realization. This demonstrates the impact of each scenario on SC profitability. It will also show how integration scenarios may result in better economic performances compared to the case when the forestry company implements the biorefinery on its own and hence, it reveals how forestry companies can benefit from the created synergies.

1. Introduction

Forestry companies have been facing an economic stalemate over the last decade due to decreasing market demand, having global low-cost competitors, lack of R&D activities, volatile/rising energy and fiber cost, etc. For a forestry company to improve its business model in the current market situation, it not only should diversify its revenue, but also must change its manufacturing culture, which currently focuses only on capacity management and neglects the profitability of the entire supply chain (SC). Revenue diversification will be achieved by producing building-block biorefinery chemicals, and ideally, in the longer term, by further increasing revenues by producing added-value derivatives, which ultimately will create a new business model. On the other side, manufacturing culture will be changed through exploiting production flexibility instead of capacity management, and by designing the SC in accordance with the needs of the new business model. In this regard, SC analysis can play a key role. In the short term, i.e. at the operational level, to mitigate the risks of market volatility, companies should focus on improving their margins by better exploiting the process capability for flexible production. SC optimization techniques can be used to carry out product planning over different time horizons and to identify tradeoffs between product orders and anticipated supply and demand. But, in order to have an appropriate performance at the operational level, the design of the SC must be carried out based on this operational-level performance. In other words, over the long term, companies should base their strategic SC-related decisions on the impact of the design decisions on operational activities. Therefore, an SC-based analysis is required in order to link these two aspects, i.e. operational and design. That being said, the challenge is to develop a SC-based analysis which can be used to reflect the SC operational performance in the SC design.

In the design of a SC, strategic long-term decisions should be made, i.e. products, technologies, number, location and capacity of each facility, e.g. plants, warehouses and distribution centres, and

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the target markets. As a result, SC-based analyses that address long-term decisions are used as a tool for analyzing and evaluating long-term strategies. Application of SC-based analysis in biorefinery design decision making is getting attention. Tursun et al. (2008) developed a mathematical programming model that determines optimal locations and capacities of biorefineries, delivery of bioenergy crops to biorefineries, and processing and distribution of ethanol and co-products across Illinois. Slade et al. (2009) analyzed the role of SC design on the viability of commercial cellulosic ethanol projects in Europe. They showed how an SC-based analysis can shed light on the major cost contributors in a project. Eksioglu et al. (2009) developed a mathematical model to analyze and manage a biomass-to-biorefinery SC. Mansoornejad et al. (2010) develop a systematic hierarchical methodology to integrate product portfolio design with SC network design in the forest biorefinery (FBR). Separate methodologies for product portfolio definition, process technology selection, and SC design are integrated in the proposed hierarchical methodology. It is described how these methodologies along with other analysis tools such as life cycle analysis (LCA) can provide criteria to be used in a multi-criteria decision-making (MCDM) framework for making the final decision. Huang et al. (2010) introduce a process model to simulate an integrated FBR manufacturing pulp and other co-products. The model has been used to compare three alternatives: the conventional Kraft pulping process, the pulp mill integrated with hemicelluloses extraction prior to pulping for ethanol production, and the pulp mill integrated with both pre-extracted hemicelluloses and the short fiber for ethanol production. Sharma et al. (2011) introduce a model for assessing the impact of feedstock and technology selection, process and utility integration, and effluent recycle for a multi-product multi-platform biorefining enterprise. Mele et al. (2011) develop a multi-objective mixed integer linear programming (MILP) that is used as a quantitative tool to support SC design decision-making and aims at optimizing the economic and environmental performance of a combined sugar and ethanol production chain. Kim et al. (2011) present a model for the optimal design of biomass SC networks under uncertainty, covering an SC located in the Southeastern region of the United States. A two stage stochastic approach is used to solve the MILP with the objective of maximizing the expected profit over the different scenarios. The robustness and global sensitivity analysis of the nominal design (for a single nominal scenario) vs. the robust design (for multiple scenarios) are analyzed using Monte Carlo simulation. Giarola et al. (2011) present an MILP framework for the strategic design and planning of corn grain and stover-based bioethanol SCs through first and second generation technologies, which optimizes the environmental and financial performances simultaneously. Bowling et al. (2011) introduce a systematic approach for the optimal production planning and facility placement of a biorefinery using an optimization formulation which specifically determines the optimal SC, size, operational strategies, location of the biorefinery and pre-processing hub facilities, and selection of biomass to maximize overall net profit. Marvin et al. (2012) study the Net Present Value (NPV) of a biomass-to-ethanol supply chain in a 9-state region in the Midwestern United States, using an MILP to find optimal locations and capacities of biorefineries in conjunction with biomass harvest and distribution. Monte Carlo simulation is performed to investigate the robustness of the SC and whether or not the proposed biorefineries will be built or will fail financially after being built. You et al. (2012) introduce a multi-objective framework which combines economic, environmental and social performance metrics, i.e. total annualized cost, greenhouse gas emissions, number of accrued local jobs, to design and plan the cellulosic ethanol SC using an MILP model.

The decision as to what biorefinery strategy to take depends on many factors, most of which cannot be reflected in an optimization problem, e.g., understanding the market and market strategies, emerging products and technologies, the capabilities of existing SC assets, and potential partners. In a practical problem, it is difficult to address all these decision within a single SC optimization model. Instead, it is preferable to pursue a systematic hierarchical methodology that addresses all these factors in a stepwise manner. Because of the combinatorial aspect of such design problems, the hierarchical methodology might miss the global optimum. However, such a methodology does not seek to identify a global optimum. Rather, it seeks a set of feasible and practical biorefinery strategies that a company can strategically pursue. Many of the key aspects can be addressed in different scenarios instead of being modeled into an optimization formulation. In this way, a simpler model will be solved, with more practical results. This methodology would end up with a set of solutions. An MCDM framework can be used to find the best strategy from a specific company's point of view.

This paper introduces a scenario-based approach for the design and analysis of SCs for the FBR using a stepwise methodology that aims at reflecting the practical aspects of design into decision making. The stepwise methodology utilizes an operational SC model to analyze the impact of design decisions on the operational level activities. SC performance metrics are introduced to quantify the performance of each design alternative at the operational level. The rest of the paper is organized as follows. First, the problem is described. Then, the proposed methodology for SC-based analysis is presented. Next, SC performance metrics and SC optimization framework, as two major tools being used in the methodology, are introduced. Afterwards, a case study is defined to concretize the methodology. Finally, some concluding remarks are drawn.

2. Problem definition

A forestry company plans to implement the biorefinery by examining the portfolio of products which secures profit, using processes which enable better response to volatile market conditions, and companies with which a partnership can be made. On one hand, market volatility must be taken into consideration, and on the other hand, possible product/process/SC network alternatives to be implemented must be identified. Scenario generation is used to address both aspects. Market conditions are reflected into the problem via market scenarios. Also, possible biorefinery alternatives, each implying a specific implementation strategy, are made in terms of alternatives, each of which includes (1) a product portfolio, (2) a technology for the production of each product, and (3) a SC network for each portfolio. For the sake of practicality, the biorefinery alternatives are defined via consultation with the forestry company which is implementing the biorefinery and based on the current status of the company in terms of exisiting SC assets, competitive position, location, etc. Given these biorefinery alternatives, an SC optimization model is used to calculate the profit of each alternative in case of several market conditions. Several market scenarios, including product price and demand change over a period of one year, are also defined as the input to the problem to represent market volatility. The SC model calculates the profitability and quantifies the flexibility of each combined alternative in case of market scenario realizations. Moreover, robustness of the SC against all market scenarios is quantified using the calculated profits.

In the following section, the hierarchical methodology is elaborated in more details.

3. Scenario-based approach for the strategic design of the SC network

The methodology proposed for scenario-based SC network design is shown in Fig. 1.

Product/Process portfolios are defined by separate methodologies. These methodologies have been reviewed by Mansoornejad et al. (2010). The output of product portfolio definition methodology is a set of product portfolios, defined as a combination of existing P&P products and new biorefinery products that can be produced by the company. The product portfolio definition methodology feeds the techno-economic study whose goal is to, first identify the process technologies that can be used to produce the targeted products, and second define different process alternatives from identified technologies with different levels of flexibility. The result will be a set of product/process portfolios that will be used as input to the methodology presented in this article. The methodology comprises of two parts; first, possible SC network alternatives are identified and after being combined with product/process portfolios, in the second part, product/process/SC network alternatives are evaluated based on their performance at the operational level. The methodology is explained in more details in the next sections.

3.1. Identify possible SC network alternatives

3.1.1. Identify the specifications of the new SC considering product options

The SC networks of forest-products companies are in place with their own existing assets. Depending on the processes used in the mills, different facilities exist on the site. However, some processing steps are common among all processes in the mill, and therefore similar facilities and assets can be used or redesigned to be able to handle larger volumes.

Biomass receiving, processing, and storage areas in the mills generally include a biomass receiving and unloading station, biomass storage with a reclaimer, biomass processing involving a biomass size-reduction process, cleaning and wet storage, and finally biomass drying and dry storage. These facilities are used regardless of the fate of the biomass, i.e. the final product. Therefore, the design process should identify whether the new processes need the same facilities and whether the existing facilities have enough capacity for the larger amount of biomass that will be brought to the mill. If new or additional facilities are required, there is a need to investigate how those facilities should be modified or be added to the site to enable the mill to accept more biomass. Moreover, existing boilers, turbines, and wastewater treatment plants can be used by the new processes, which will significantly reduce the required capital cost for implementing the FBR (Janssen et al., 2008).

On the product side, the characteristics of new products must be taken into account to redesign the SC network. Each product has specific properties and characteristics which imply specific facilities for transportation and storage. Some products can be stored in warehouses, while others must be stored in tanks. Moreover, some products are transferred by truck or train, while others should be transported in a tanker or by pipeline. Therefore, the specifications of each product must be identified so that they can be addressed when defining SC network alternatives.

3.1.2. Define SC network alternatives

With the existing SC assets and the characteristics of the products, the specifications of the new SC network can be identified. Based on these specifications, several SC network alternatives can be defined, which reflect the needs of the new SC network as well as the concerns of company experts. Thus, the alternatives are defined via discussion with company's representatives. Several issues should be addressed when generating these alternatives;

- Partnership: Collaborating with other companies whose expertise brings value to the company's business model must be considered in the SC network design. Partners can cooperate in producing a product, delivering the product, buying the product, and/or selling the product to the market. In this way, a part of the partner's SC assets will be used, and less capital will be needed for establishing the new SC network.
- Location and capacity of distribution centers: based on the location of the plant, several target markets might exist in the areas around the plant. Therefore, different distribution centers with different capacities can be assigned to the target market areas. The role of partners in this issue is important. They might take the role of seller in the target markets, and they might have the required infrastructure for this purpose.
- Transportation network: Based on the characteristics of the products, different means of transportation can be used for product delivery. Again, partnerships can be used to reduce the capital costs required for establishing a transportation network.

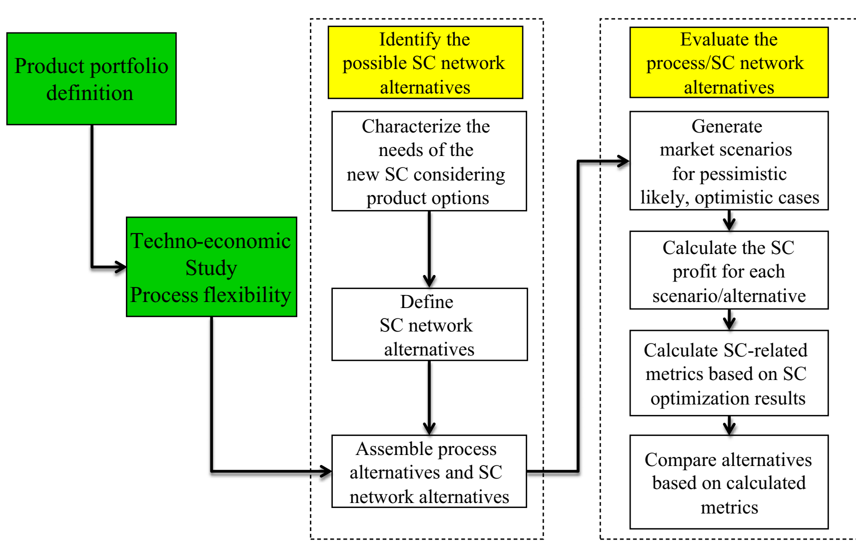

Fig. 1. Scenario-based methodology for the SC network design.

Contracts can be made with transportation companies which have a network of trucks or tankers and can simply deliver the products to markets. In addition, partners which buy the products or just deliver them to the market might have their own existing transportation network.

3.1.3. Assemble process alternatives and SC network alternatives

After defining the SC network alternatives, the product/process alternatives are assembled to create combined alternatives. Each combined alternative involves a process configuration with a targeted flexibility level and a SC network related to the products. The capital investment required to redesign the SC network is added to the capital investment needed for the process technologies for each alternative. The capital investment needed for the SC network alternatives which involve partnerships is smaller because a part of capital will be paid or has already been paid by the partner. However, it should be noted that the revenue will also be shared by the partner, and therefore less profit will be acquired by the company.

3.2. Evaluate the process design/SC network alternatives

3.2.1. Generate price/supply/demand scenarios

To address the uncertainty of market conditions and to reflect market volatility in the decision-making process, a scenario-based approach is used. Each scenario represents a specific market condition with respect to price, supply, and demand. Scenarios are generated in terms of feedstock supply and product demand, as well as feedstock and product prices. Scenarios must be generated to capture different market situations, that is, pessimistic, likely, and optimistic cases should be considered in scenario generation. Another important factor in scenario generation is the time aspect. Scenarios can be generated for different time scales, and depending on the type of decisions to be made in the scenario analysis, scenarios can be generated for the short, medium, or long term. For strategic design-related decisions, scenarios should be generated for the long term, e.g., for a period of several year. As supply, demand, and price change during the year, the values associated with them can vary on a monthly or seasonal basis. Note that buying feedstock and selling products can be done based either on contracts or on the spot market. Contractual prices and demands imply fixed values during specific periods, meaning that the amount of product and its price in the contract can be fixed for the whole period of the contract, while spot prices are generally subject to changes based on the market situation. Therefore, both spot and contractual prices and demands must be addressed in scenario generation. Market scenarios can be defined through a market analysis, which is not in the scope of this work.

3.2.2. Calculate the SC profit for each scenario/alternative

To evaluate combined alternatives, the profitability of each alternative along with other metrics must be estimated. Therefore, the SC profit associated with each alternative in different market situations must first be calculated, and then, using the profit, profitability of each alternative as well as other metrics can be estimated. In this step, the SC profit for each product/process/SC alternative is calculated for every price/supply/demand scenario. To calculate the SC profit, the SC optimization model is used. The model optimizes SC profit by determining which orders to fulfill and calculating the optimum value of production rate related to each product and the flows of material between SC nodes. The overall problem at this stage can be stated as follows. Given:

- Number and length of time intervals
- Demand and price data for each feedstock, product, market, and time interval for each scenario
- Process configuration based on what was defined in the process design alternatives
- Configuration of the SC network based on what was defined in the SC network alternatives
- Capacity data of the nodes of the SC
- Direct cost parameters, i.e. unit production, transport, handling, and inventory costs based on operating cost calculations.

With the aim of profit maximization, find

- Orders to fulfill: which contracts to make, which spot demand to fulfill
- Production rates of each product for all time intervals and all market scenarios
- Flows of materials between the plants, warehouses, distribution centers, and markets
- SC profit.

3.2.3. Calculate SC-related metrics based on SC optimization results

To evaluate each product/process/SC alternative, the value of several metrics should be estimated for each alternative. In this paper, SC profitability, flexibility and robustness are used as SC-related metrics. Profit and profitability have always been major metrics for analyzing the economic performance of a system. Furthermore, with regards to today's volatile market, it is important to apply metrics that can quantify the performance of a system against market volatility. This is why metrics of flexibility and robustness are introduced in this paper. Metric of flexibility quantifies the potential for flexibility in a system in different market conditions, while metric of robustness reveals how robust the system will be in a volatile market.

There are several profitability estimation methods that can be used to estimate the profitability of a project. In this methodology, internal rate of return (IRR) is used as the measure of profitability. IRR is defined as the discount rate at which sum of discounted cash flows over a period becomes zero. Cash flow is calculated as the net profit minus tax. The net profit is the objective function of the optimization model and is calculated by that. Using the capital cost and net profit, the IRR can be calculated.

It is worth noting that profitability still plays the key role in decision-making in industrial projects. Companies would like to identify the most profitable alternatives/strategies and then to see which one is the most robust or flexible among them. For this reason, metrics of flexibility and robustness are only used as quantifying metrics and are not used directly in the objective function.

Metrics of flexibility and robustness are explained in Section 4.

3.2.4. Compare alternatives based on calculated metrics

The calculated metrics can be used to decide which alternative has better performance against market volatility and is more profitable over the long term. As mentioned earlier, the SC optimization plays the role of a tool that provides better insight into the problem. It does not aim at making the final decision and it is the human knowledge and experience that make the final decision. When having several metric/criteria, an MCDM framework can be helpful. It uses several metrics provided by different analysis tools such as SC analysis, LCA, techno-economic studies, etc, and evaluates the performance of the system from different perspectives and identify the best alternative based on that. However, performing the MCDM is out of the scope of this work and only the results coming out of the SC analysis are presented.

4. SC performance metrics

As stated by Beamon (1998), establishment of appropriate performance measures is an important component in SC design and analysis. Performance measures can be used either in comparing competing alternative systems, or in designing proposed systems, by determining the values of the decision variables that yield the most desirable level(s) of performance. These measures can be classified into two categories; qualitative and quantitative. Qualitative performance measures are those measures for which there is no single direct numerical measurement, although some aspects of them may be quantified. Customer satisfaction, flexibility, information and material flow integration, effective risk management, supplier performance are example of qualitative measures. On the other hand, quantitative performance measures may be defined numerically. Such measures may be described by, either objectives that are based directly on cost or profit such as cost minimization, sales maximization, profit maximization, inventory investment minimization, return on investment maximization, or objectives that are based on some measure of customer responsiveness like fill rate maximization, product lateness minimization, customer response time minimization, lead time minimization, function duplication minimization.

In this work, two metrics are used to evaluate the performance of SC in volatile market; metric of flexibility (MF) and metric of robustness (MR). These metrics are not part of the decision variables of the SC model, and thus, they are not optimized. They are just calculated and used to quantify the flexibility and robustness of SC in volatile market conditions.

4.1. Metric of flexibility (MF)

Beamon (1998) defined the measure of flexibility as the degree to which the supply chain can respond to random fluctuations in the demand pattern. This is a generic definition and involves all types of flexibility. In systems engineering, many works are done on the issue of flexibility based on the work of Swaney and Grossmann (1985). They defined flexibility index as a metric that characterizes the size of the region of feasible operation in the uncertain parameter space. Another measure of flexibility was introduced by Voudouris (1996) which defines flexibility as the ability of the system to absorb unexpected demand. The importance of flexibility has been considered by many researchers. Garavelli (2003) proposed a simulation model to evaluate the performance of different flexibility configurations of an SC. Tang and Tomlin (2008) addressed the problem of determining the level of flexibility for mitigating SC risks. Merschmann and Thonemann (2011) studied the relationship between environmental uncertainty, supply chain flexibility, and firm performance. Wallace and Choi (2011) concretized the concept of robustness, flexibility, information structure, options, and market power in supply chain management context.

In this paper, a metric of flexibility is presented that can be well applied for design purposes for the FBR design. In the design of chemical processes, volume flexibility has a critical role. Thus, in order to design or analyse the flexibility of a system, quantifying volume flexibility is of crucial importance. Inspired by the work of Voudouris (1996) on qualitative measure of flexibility, metric of flexibility (MF) quantifies volume flexibility, as shown in Eq. (1)

$$MF = \sum_p \sum_m \frac{\Sigma_t |C_{mpt} - C^N_{mp}|}{\Sigma_t C^N_{mp}} \quad (1)$$

where C_{mpt} is the amount of product m that is produced on process p in time period t and C^N_{mp} is the amount of product m produced on process p by the nominal production rate over the same number of processing hours. This formulation shows the deviation from the nominal production rate in a dimensionless form and implies volume flexibility.

4.2. 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 (Bernardo et al. 1999). In this work, robustness is not considered in the optimization formulation. Instead, a metric of robustness (MF) is used to

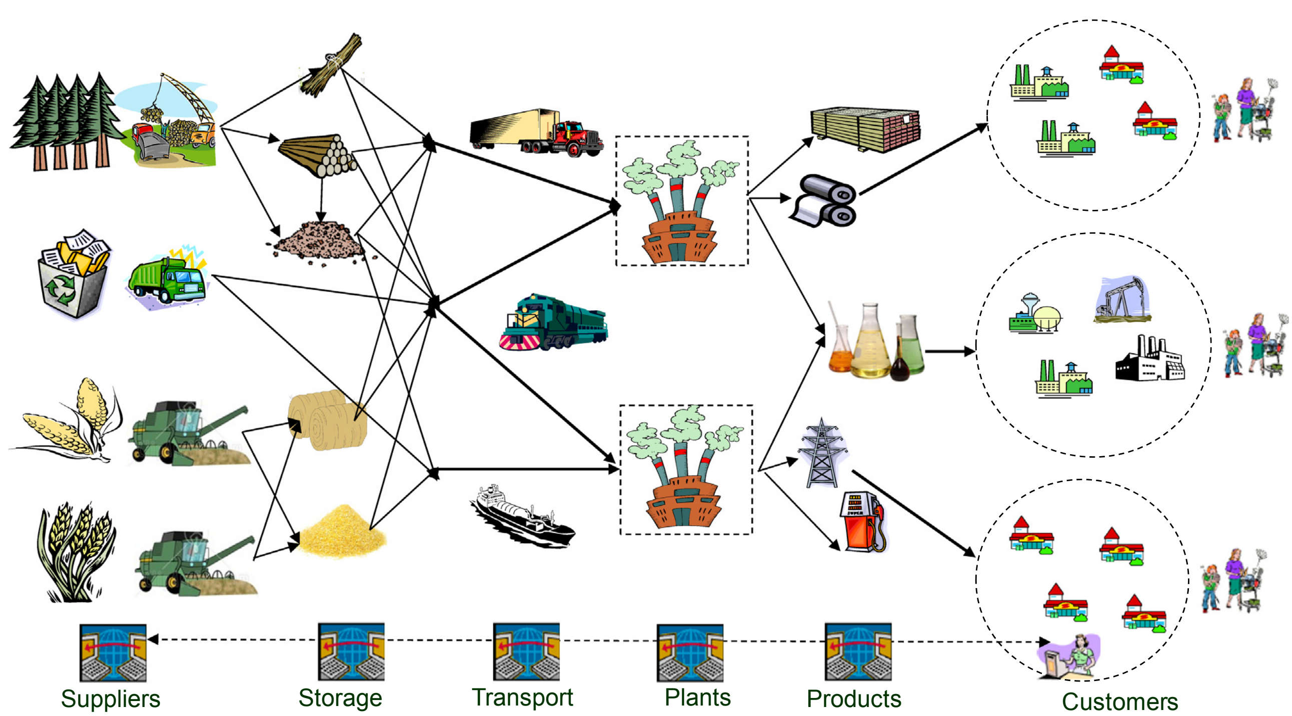

Fig. 2. Forest biorefinery supply chain.

quantify the robustness of design alternatives against market volatility so that design alternatives can be compared in terms of robustness. Several robustness metrics have been introduced thus far (Vin and Ierapetritou, 2001). Well-known metrics are standard deviation and mean absolute deviation (Bernardo et al., 2001). For the sake of simplicity and interpretability for an MCDM panel, we use a simple formulation as robustness metric, as shown in Eq. (2).

$$\mathrm{MR} = \left(\frac{\sum_{Sc}(\mathrm{Pr}_B - \mathrm{Pr}_{Sc})}{Pr_B}\right)^{-1} \tag{2}$$

where Pr_B is the base case profit, Pr_{Sc} is the profit for scenario Sc and N_{Sc} is the number of scenarios. In this work, the desired parameter that must not diverge from a given value is profit. It is desirable that the profit of a design alternative in case of each market scenario does not deviate from the base case profit, if this profit is lower than the base case profit, i.e. a downside profit. Therefore, to quantify the downside risk of volatility, the downside profits are considered in this equation. The MR shows the percentage of aggregate deviation from the base case profit for all downside profits. The smaller this percentage is the better and more robust the system is. Hence, the reverse of the percentage was used so that the higher values of MR represent more robust systems.

5. SC optimization framework

Fig. 2 illustrates the SC of an FBR. Several types of feedstock, ranging from forest biomass to recycled papers and agricultural residues, can be used. Feedstock is treated and prepared to be used in the plants. The final products involve wood and paper products, biofuel, green chemicals and energy.

There is a strong body of knowledge related to SC mathematical formulation. Such formulations address strategic design, tactical planning or operational and scheduling SC decisions. Some examples can be viewed in Voudouris (1996), Timpe and Kallrath (2000), Jin-Kwang et al. (2000), Tsiakis et al. (2001), Sousa et al. (2005), and You and Grossmann (2008).

The SC framework aims at maximizing profit across the entire SC by identifying the tradeoffs between demand and production capabilities and by finding the optimal alignment of manufacturing capacity and market demand. The SC optimization framework considers feedstock price and availability, production costs, and inventory and delivery costs, as well as product price and demand. Taking this information into account, the SC optimization framework will exploit the potential for production flexibility and determine which orders must be fulfilled and therefore how much of which products must be produced, how they should be stored, and how they should be delivered to the market to maximize SC profit.

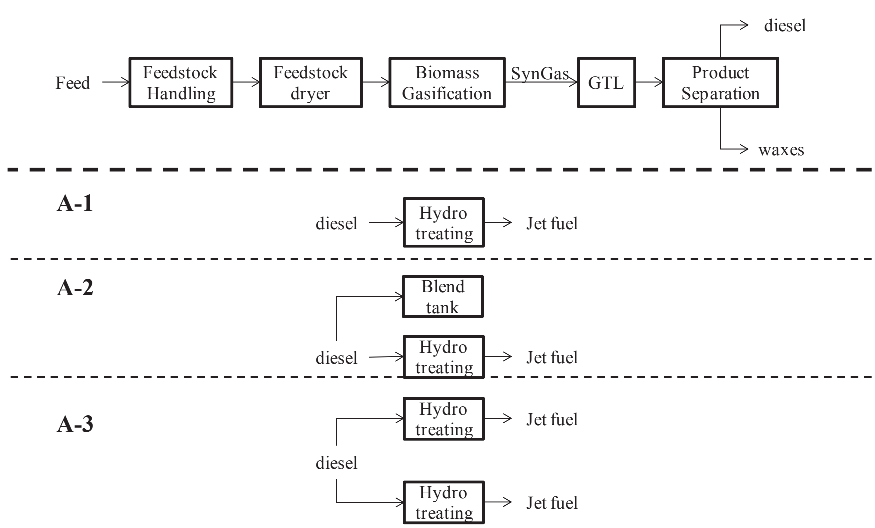

Fig. 3. Design alternatives for thermochemical option.

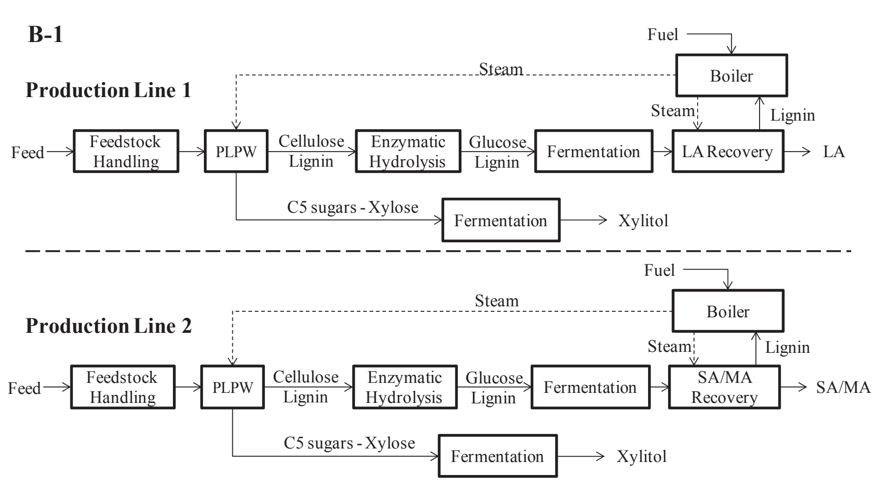

Fig. 4. 1st process alternative for biochemical option.

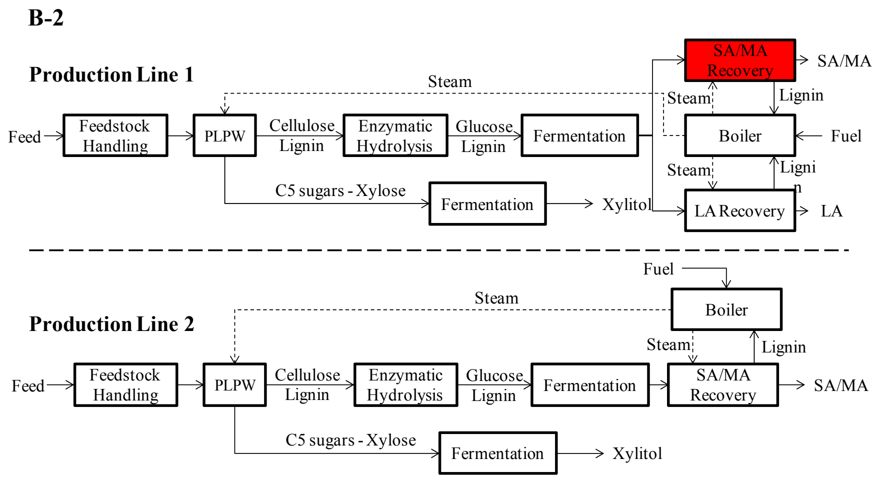

Fig. 5. 2nd process alternative for biochemical option.

Table 1
SC network alternatives defined for portfolio 1.

	A-1	A-2	A-3
Processing	Partnership with JF producer **OR** Producing JF at the mill	Producing JF at the mill	Producing JF at the mill
Selling	Waxes: Contract & Spot Diesel: To JF producer **OR** To be converted to JF Jet fuel: Contract	Waxes: Contract & Spot Diesel: Contract with a partner **OR** Spot Jet fuel: Contract	Waxes: Contract & Spot Diesel: Contract & Spot Jet fuel: Contract & Spot
Warehousing	Expansion	Expansion	Expansion
Delivery/transportation	Wax delivery Buy trucks Partnership for JF delivery	Wax and diesel delivery Buy trucks Partnership for JF delivery	Wax and diesel delivery Buy trucks **OR** Contract with a partner Partnership for JF delivery

It is desirable to account for tactical and operational issues at the strategic design level. On the other hand, for design purposes, it is not necessary to go down to too much details, as provided by scheduling models. For this reason, the SC framework that is presented in this work is inspired by the tactical model developed for the chemical industry by Kannegiesser (2008). This model is a tactical model that has some operational components. The model divides each time period into several hours that can be dedicated to production, changeover or maintenance. In this way, a better cost representation can be made by the model.

The SC framework is formulated as an optimization problem with the objective of maximizing profit. This framework considers the management of a multi-product, multi-echelon SC, including existing production and warehousing facilities as well as a number of customer zones, although it can also be used for design purposes. Different types of biomass are provided by several suppliers. Production facilities can make one or several products. Processes are either dedicated, i.e. they produce only one product, or flexible from a product perspective, i.e. they are able to produce several products through different recipes. In other words, a flexible process can use different recipes to produce different products. Changing from one recipe to another incurs changeover cost and time. Processes can be idled or shutdown for scheduled maintenance. The steam required for each process is provided by both fuel and biomass. Warehouses can receive material, either feedstock or product, 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 in the spot market, 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 problem with a discrete time horizon of 48 weeks. Each time period is broken down into hours. Several subsets have been created to link parameters and variables to each other. For instance, some customers will only accept products from specific mills. Processes can only produce certain materials. This will reduce the possible options and thus, the complexity of the problem. The model is presented below:

5.1. Nomenclature

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

Suppliers that can supply mill	$\{j,l\} \in L^{JL} \quad \forall\, j \in J,\ l \in L$

Customers that can be served by mill	$\{l,k\}\in L^{LK} \quad \forall\ l\in L, k\in K$
Processes at mill	$\{l,p\}\in P^{L} \quad \forall\ l\in L, p\in P$
Recipes available on process	$\{l,p,r\}\in R^{P} \quad \forall\ \{l,p\}\in P^{L}, r\in R$
Materials offered by suppliers	$\{j,m\}\in M^{J} \quad \forall\ j\in J, m\in M$
Materials produced/ processed at mill	$\{l,m\}\in M^{L} \quad \forall\ l\in L, m\in M$
Materials requested by customers	$\{k,m\}\in M^{K} \quad \forall\ k\in K, m\in M$
Input materials of a process	$\{l,p,m\}\in M^{P-in} \quad \forall\ \{l,p\}\in P^{L}, m\in M$
Output materials of a process	$\{l,p,m\}\in M^{P-out} \quad \forall\ \{l,p\}\in P^{L}, m\in M$
Input materials of a recipe	$\{l,p,r,m\}\in M^{r-in} \quad \forall \{l,p,r\}\in R^{P}, m\in M$
Output materials of a recipe	$\{l,p,r,m\}\in M^{r-out} \quad \forall\ \{l,p,r\}\in R^{P}, m\in M$

Constructed Subsets

Materials that can be transported between a supplier and a mill:	$\{j,l,m\}\in M^{JL} \quad \forall\ \{j,l\}\in L^{JL}, \{j,m\}\in M^{J}, \{l,m\}\in M^{L}$
Materials that can be transported between a mill and a customer:	$\{l,k,m\}\in M^{LK} \quad \forall \{l,k\}\in L^{LK}, \{l,m\}\in M^{L},\ \{k,m\}\in M^{K}$

Parameters

a_{lprm}^{input}	Recipe material conversion Input factor of material m when using recipe r on process p in mill l (dependent on throughput) [ton/ton or GJ/GJ for boilers]
a_{lprm}^{output}	Output factor of material m when using recipe r on process p in mill l [ton/ton]
$b_{lpr}^{input-steam}$	Steam consumption factor for recipe r in process p in mill l [GJ/ton for processes, GJ/GJ for boilers]
$b_{lpr}^{output-steam}$	Steam production factor for recipe r in process p in mill l [GJ/ton]
$b_{lpr}^{input-elect}$	Electricity consumption factor for recipe r in process p in mill l [kW h/t]
$b_{lpr}^{output-elect}$	Electricity production factor for recipe r in process p in mill l [kW h/GJ steam]
$c_{lpr}^{proc-\mathrm{var}}$	Variable operating cost of using recipe r on process p in mill l (dependent on process throughput) [$/t]
$c_{lt}^{mill-fix}$	Fixed operating cost at mill l during time period t [$]
$c_{jlm}^{transport-\mathrm{sup}}$	Transportation cost of material m from supplier j to mill l [$/t]
$c_{lkm}^{transport-sales}$	Transportation cost of material m from mill l to a customer k [$/t]
c_{lm}^{stor}	Storage cost of material m in mill l [$/t]
$c_{lp}^{shutdown}$	Shutdown cost of process p in mill l [$/h]
$c_{lp}^{changeover}$	Changeover cost of process p in mill l [$]
c_{lt}^{elect}	Electricity cost/ selling price at mill l during time period t [$/kW h]
c_{kmt}^{sales}	Selling price of product m to customer k during time period t [$/t]
c_{jmt}^{sup}	Purchasing price of a feedstock m from supplier j during time period t [$/t]
$c_{kmt}^{salescost}$	Sales cost for product m sold to customer k during time period t [$/t]
H_{lpr}^{camp}	Minimum campaign length for recipe r in process p in mill l [h]
$H_{lp}^{changeover}$	Changeover time on process p in mill l [h]
H_{lpt}^{proc}	Available processing hours on process p in mill l during time period t [h]
$\underline{Q}_{lpr}^{proc}$	Minimum throughput of recipe r on process p in mill l [t/h]
$\overline{Q}_{lpr}^{proc}$	Maximum throughput of recipe r on process p in mill l [t/h]
$\underline{Q}_{lm}^{stor}$	Minimum storage quantity of material m in mill l [ton]
$\overline{Q}_{lm}^{stor}$	Maximum storage quantity of material m in mill l [ton]
$\underline{Q}_{jmt}^{supp}$	Minimum supply quantity of material m offered by supplier j during time period t [ton]
$\overline{Q}_{jmt}^{supp}$	Maximum supply quantity of material m offered by supplier j during time period t [ton]
$\underline{Q}_{kmt}^{sales}$	Minimum quantity of material m requested by customer k during time period t [ton]
$\overline{Q}_{kmt}^{sales}$	Maximum quantity of material m requested by customer k during time period t [ton]
$\overline{Q}_{jlm}^{transport-sup}$	Maximum transportation quantity of material m between supplier j and mill l [ton]
$\overline{Q}_{lkm}^{transport-sales}$	Maximum transportation quantity of material m between customer k and mill l [ton]
$S_{lm}^{mat-start}$	Initial storage quantity of material m in mill l at time 0 [ton]
$S_{lm}^{mat-end}$	Minimum storage quantity of material m in mill l at time T [ton]
ε_{lpt}^{proc}	Shutdown hours on process p in mill l during time period t [h]
α_{lpr}^{start}	Initial recipe r on process p in mill l

Variables

f_{jlmt}^{sup}	Flow of material m from supplier j to mill l during time period t [ton]
f_{lkmt}^{sales}	Flow of material m from mill l to customer k during time period t [ton]
h_{lprt}^{rec}	Number of hours spent on recipe r on process p in mill l during time period t [h]
S_{lmt}^{mat}	Inventory of material m in mill l during time period t [ton]
v_{lpt}^{input}	Input steam quantity on process p in mill l during time period t [GJ]
v_{lpt}^{output}	Output steam quantity on process p in mill l during time period t [GJ]
w_{lpt}^{input}	Input electricity quantity on process p in mill l during time period t [kW h]
w_{lpt}^{output}	Output electricity quantity on process p in mill l during time period t [kW h]

x^{proc}_{lmpt}	Input quantity of material m on process p in mill l during time period t [ton]
y^{proc}_{lmpt}	Output quantity of material m on process p in mill l during time period t [ton]
y^{rec}_{lprmt}	Output quantity of material m using recipe r on process p in mill l during time period t [ton]
$y^{rec-tot}_{lprt}$	Total mass output of recipe r on process p in mill l during time period t [ton]
α^{rec}_{lprt}	Selection of recipe r on process p in mill l during time period t (binary)
β^{proc}_{lprt}	Successive selection of recipe r on process p in mill l during time periods t and t-1 (binary)
θ^{ord}_{kmt}	Selection of the order of product m from customer k during time period t (binary)

5.2. Objective function

The objective function is the global net profit of the enterprise to be maximized. This profit consists of revenues from the sales of products and electricity, minus several variable and fixed costs.

$$\max \text{Profit} = \left(\begin{array}{c} \text{Revenues} - \text{ElectricityCost} - \text{SalesCost} \\ -\text{VariableOpCost} - \text{FixedOpCost} - \text{ChangeoverCost} - \text{ShutdownCost} \\ -\text{TransportationCost} - \text{StorageCost} - \text{ProcurementCost} \end{array} \right) \tag{3}$$

Revenues from sales are equal to the flow of materials sent to each customer multiplied by the selling price.

$$\text{Revenue} = \sum_{t\in T} \sum_{\{l,k,m\}\in M^{LK}} f^{sales}_{lkmt} c^{sales}_{kmt} \tag{4}$$

Electricity sales or purchases are function of the production/consumption at the mill. If the mill produces more electricity than needed, then electricity is sold to the grid. Otherwise, it is assumed it is bought from the grid at the same price.

$$\text{ElectricityCost} = \sum_{t\in T} \sum_{\{l,p\}\in P^{L}} (w^{input}_{lpt} - w^{output}_{lpt}) c^{elect}_{lt} \tag{5}$$

Variable sales costs are customer specific and are a percentage of product prices.

$$\text{SalesCost} = \sum_{t\in T} \sum_{\{l,k,m\}\in M^{LK}} f^{sales}_{lkmt} c^{salescost}_{kmt} \tag{6}$$

Variable operating costs are a function of process throughput such as chemical consumption.

$$\text{VariableOpCost} = \sum_{t\in T} \sum_{\{l,p,r\}\in R^{P}} c^{proc-var}_{lpr} y^{rec-total}_{lprt} \tag{7}$$

Fixed operating costs are calculated at the plant.

$$\text{FixedOpCost} = \sum_{t\in T} \sum_{l\in L^{mill}} c^{mill-fix}_{lt} \tag{8}$$

Changeover cost is equal to the number of transitions multiplied by the changeover cost per transition. This cost is not considered sequence dependent.

$$\text{ChangeoverCost} = \sum_{t\in T} \sum_{\{l,p,r\}\in R^{P}} (1 - \sum_{r\in R^{proc}_{p}} \beta^{proc}_{lprt})\, c^{changeover}_{lp} \tag{9}$$

The shutdown cost of a process is a function of the number of shutdown hours during a time period. Scheduled shutdowns for maintenance are considered here as a hard constraint.

$$\text{ShutdownCost} = \sum_{t\in T} \sum_{\{l,p\}\in P^{L}} \varepsilon^{proc}_{pt} c^{shutdown}_{lp} \tag{10}$$

Transportation cost is calculated by multiplying the amount of material shipped from a source (supplier j or mill l) to a sink (mill l or customer k) and the shipping cost per mass of that route.

$$\text{TransportationCost} = \sum_{t\in T} \sum_{\{j,l,m\}\in M^{JL}} f^{sup}_{jlmt} c^{transport-sup}_{jlm} + \sum_{t\in T} \sum_{\{l,k,m\}\in M^{LK}} f^{sales}_{lkmt} c^{transport-sales}_{jlm} \tag{11}$$

Storage cost in a facility is equal to the amount of material kept in inventory during each time period multiplied by its storage cost per month.

$$\text{StorageCost} = \sum_{t\in T} \sum_{\{m,l\}\in M^{L}} S^{mat}_{mlt} c^{stor}_{lm} \tag{12}$$

Procurement costs are equal to the flow of materials transported from each supplier to different facilities multiplied by the selling price.

$$\text{ProcurementCost} = \sum_{t\in T} \sum_{\{j,l,m\}\in M^{JL}} f^{sup}_{jlmt} c^{sup}_{lmt} \tag{13}$$

5.3. Demand and procurement

Suppliers and customers may offer/request materials between lower and upper fulfilment bounds, as shown in Eqs. (14) and (15). Lower and upper bounds for customers are multiplied by binary variable θ, which is equal to one if the order is fulfilled and equal to zero otherwise. For contractual orders, the lower and upper bounds are equal, because the contractual amount is fixed. But the lower bound for spot orders is equal to zero and the model can determine what percentage of the order should be fulfilled. Eq. (16) forces θ of all time periods to be equal to θ of first time period. In this way, if an order is accepted in the first period, it must be fulfilled over all other time periods. This constrain refers to contractual orders, which either must be fulfilled throughout the year, or must be refused. This will not cause any problem for spot orders, which can be fulfilled partially at any time, because if model decides not to fulfil a spot order, model can assign zero to fulfilled amount for this order, as the lower bound for spot order fulfilment is zero, no matter if θ is zero or one. Thus, it can be said that θ is one for all spot orders and can be zero or one for contractual orders.

$$\underline{Q}^{supp}_{lmt} \le f^{sup}_{jlmt} \le \overline{Q}^{supp}_{lmt} \qquad \forall \{j,l,m\} \in M^{LJ},\ t\in T \tag{14}$$

$$\theta^{ord}_{kmt} \underline{Q}^{sales}_{lmt} \le f^{sales}_{lkmt} \le \theta^{ord}_{kmt} Q^{sales}_{lmt} \qquad \forall \{l,k,m\} \in M^{LK}, t\in T \tag{15}$$

$$\theta^{ord}_{km1} = \theta^{ord}_{kmt} \qquad \forall \{l,k,m\} \in M^{LK}, t>1 \tag{16}$$

5.4. Transportation

A maximum transportation capacity constraint limits the amount of materials that can be transported between locations (suppliers, facilities and customers).

$$f^{sup}_{jlmt} \le \overline{Q}^{transport-sup}_{jlm} \qquad \forall \{j,l,m\} \in M^{LJ},\ t\in T \tag{17}$$

$$f^{sales}_{lkmt} \le \overline{Q}^{transport-sales}_{lkm} \qquad \forall\ \{l,k,m\} \in M^{LK}, t\in T \tag{18}$$

5.5. Inventory management

The material balance at a facility is equal to the previous inventory, plus/minus material coming from and going to other sites as well as the consumption/production from processes.

$$S^{mat}_{mlt} = S^{mat}_{mlt-1} + \sum_{\{j,l,m\}\in M^{JL}} f^{sup}_{jlmt} - \sum_{\{l,k,m\}\in M^{LK}} f^{sales}_{lkmt}$$

Table 2
SC network alternatives defined for portfolio 2.

	B-1	B-2
Processing	Send extractives to partner **OR** Process extractives at the mill	Send extractives to partner **OR** Process extractives at the mill
Selling	SA: Contract & Spot MA: Contract & Spot LA: Contract & Spot	SA: New market for Contract & Spot MA: Contract & Spot LA: Contract & Spot
Warehousing	Expansion	Expansion
Delivery/Transportation	Buy trucks **OR** Contract with a logistics partner	Partnership for SA delivery/selling Buy trucks **OR** Contract with a logistics partner

Table 3
Capital investment of combined alternatives.

Portfolio 1			Portfolio 2		
Process alternative	**SC network alternative**	**Capital ($MM)**	**Design alternative**	**SC network alternative**	**Capital ($MM)**
A-1	Partner for JF	61	**B-1**	Sell extractives	113
	Produce JF	87		Process extractives	122
A-2	Diesel on spot	78	**B-2**	Sell extractives	122
	Partner for diesel	76		Process extractives	131
A-3	Own fleeting	98			
	Partnership	95			

$$-\sum_{\{l,p,m\}\in M^{P-out}} x^{proc}_{lmpt} + \sum_{\{l,p,m\}\in M^{P-in}} y^{proc}_{lmpt} \qquad \forall\{l,m\}\in M^L, t>1 \tag{19}$$

At time $t=1$, S^{mat}_{mlt-1} does not exist and it is replaced by the initial inventory quantity, S^{start}_{ml}.

$$S^{mat}_{ml1} = S^{mat-start}_{ml} + \sum_{\{j,l,m\}\in M^{JL}} f^{sup}_{jlm1} - \sum_{\{l,k,m\}\in M^{LK}} f^{sales}_{lkm1} - \sum_{\{l,p,m\in M^{P-out}\}} x^{proc}_{lmp1} + \sum_{\{l,p,m\}\in M^{P-in}} y^{proc}_{lmp1} \qquad \forall\{l,m\}\in M^L, t=1 \tag{20}$$

To ensure that the optimization model does not completely deplete the inventory at the end of the planning horizon ($t=T$), a constraint specifying the final minimum inventory quantity must be added.

$$S^{mat}_{mlt} \ge S^{mat-End}_{ml} \qquad \forall\{l,m\}\in M^L, t=T \tag{21}$$

Finally, each site has storage capacity constraints.

$$\underline{Q}^{stor}_{lm} \le S^{mat}_{lmt} \le \overline{Q}^{stor}_{lm} \qquad \forall\{l,m\}\in M^L,\ t\in T \tag{22}$$

5.6. Recipe selection

Eqs. (23)–(28) constrain the selection of recipes. Each process has an offline/idle recipe that can be selected for when the process is not needed. Eq. (23) demands that only one recipe (campaign) must be selected during one time period.

$$1 = \sum_{\{l,p,r\}\in R^P} \alpha^{rec}_{lprt} \qquad \forall\{l,p\}\in P^L, t\in T \tag{23}$$

Eq. (24) determines the recipes that are used in the first time period.

$$\alpha^{start}_{lpr} \le \alpha^{rec}_{lprt} \qquad \forall\{l,p,r\}\in R^P, t=1 \tag{24}$$

Eqs. (25)–(28) define binary variable β which represents the recipes that are used in at least two consecutive time periods. In the first time period β is equal to zero, as there is no time period before this period. Eqs. (26)–(28) make the linkage between α and β. Eqs. (27) and (28) ensure that β is zero, if α is zero in the same or previous time period.

$$\beta^{proc}_{lprt} = 0 \qquad \forall\{l,p,r\}\in R^P,\ t=1 \tag{25}$$

$$\alpha^{rec}_{lprt} + \alpha^{rec}_{lprt-1} - 1 \le \beta^{proc}_{lprt} \qquad \forall\{l,p,r\}\in R^P,\ t\in T \tag{26}$$

$$\beta^{proc}_{lprt} \le \alpha^{rec}_{lprt-1} \qquad \forall\{l,p,r\}\in R^P,\ t\in T \tag{27}$$

$$\beta^{proc}_{lprt} \le \alpha^{rec}_{lprt} \qquad \forall\{l,p,r\}\in R^P,\ t\in T \tag{28}$$

5.7. Production

Processes must be permanently utilized (or idled) during a time period. The available processing hours are equal to the number of hours during a time period minus scheduled maintenance shutdown and lost time during changeovers. As there is no changeover in the first time period, Eq. (29) only considers shutdown hours.

$$\sum_{\{l,p,r\}\in R^P} h^{rec}_{lprt} = H^{proc}_{lpt} - \varepsilon^{proc}_{lpt} \qquad \forall\{l,p\}\in P^L,\ t=1 \tag{29}$$

$$\sum_{\{l,p,r\}\in R^P} h^{rec}_{lprt} = H^{proc}_{lpt} - \varepsilon^{proc}_{lpt} - \left(1 - \sum_{\{l,p,r\}\in R^P} \beta^{proc}_{lprt}\right) H^{changeover}_{lp} \qquad \forall\{l,p\}\in P^L,\ t\in T>1 \tag{30}$$

Each recipe has minimum and maximum throughput boundaries (tons/h).

$$h^{rec}_{lprt}\underline{Q}^{proc}_{lpr} \le y^{rec-tot}_{lprt} \le h^{rec}_{lprt}\overline{Q}^{proc}_{lpr} \qquad \forall\{l,p,r\}\in R^P, t\in T \tag{31}$$

Production hours are bounded between minimum campaign length and available processing hours including shutdown hours.

$$\alpha^{rec}_{lprt} H^{camp}_{lpr} \le h^{rec}_{prt} \qquad \forall\ l\in L^{mill}, p\in P^{mill}_l, r\in R^{proc}_p, t\in T \tag{32}$$

$$h^{rec}_{lprt} \le \alpha^{rec}_{lprt}(H^{proc}_{lpt} - \varepsilon^{proc}_{lpt}) \qquad \forall\ l\in L^{mill}, p\in P^{mill}_l, r\in R^{proc}_p, t\in T \tag{33}$$

Eqs. (34)–(36) are related to the mass balance. Eq. (34) links the material conversion from feedstock to products. Linear recipe functions are used to represent process where raw material consumption depends on the utilization rate of the equipment employed. Eq. (35) relates the material output to the total output

Fig. 6. Market scenarios for the Thermochemical option.

of a process, while Eq. (36) aggregates the total output of a material during one time period.

$$x_{lmpt}^{proc} = \sum_{\{l,p,r,m\}\in M^{R-in}} a_{lprm}^{input} y_{lprt}^{rec-tot} \qquad \forall \{l,p,m\} \in M^{P-in}, t\in T \tag{34}$$

$$y_{lprmt}^{rec} = a_{lprm}^{output} y_{lprt}^{rec-tot} \qquad \forall \{l,p,r\}\in R^{P}, \{l,p,r,m\}\in M^{R-out}, t\in T \tag{35}$$

$$y_{lmpt}^{proc} = \sum_{\{l,p,r,m\}\in M^{R-out}} y_{lprmt}^{rec} \qquad \forall \{l,p,m\}\in M^{P-out}, t\in T \tag{36}$$

Processes require or produce steam and/or electricity for their operation. Eqs. (37)–(40) calculate the steam and electricity production/consumption of processes based on the recipe used.

$$v_{lpt}^{output} = \sum_{\{l,p,r\}\in R^{P}} b_{lpr}^{output-steam} y_{lprt}^{rec-tot} \qquad \forall \{l,p\}\in P^{L}, t\in T \tag{37}$$

$$v_{lpt}^{input} = \sum_{\{l,p,r\}\in R^{P}} b_{lpr}^{input-steam} y_{lprt}^{rec-tot} \qquad \forall \{l,p\}\in P^{L}, t\in T \tag{38}$$

$$w_{lpt}^{output} = \sum_{\{l,p,r\}\in R^{P}} b_{lpr}^{output-elect} v_{lpt}^{output} \qquad \forall \{l,p\}\in P^{L}, t\in T \tag{39}$$

$$w_{lpt}^{input} = \sum_{\{l,p,r\}\in R^{P}} b_{lpr}^{input-elect} y_{lprt}^{rec-tot} \qquad \forall \{l,p\}\in P^{L}, t\in T \tag{40}$$

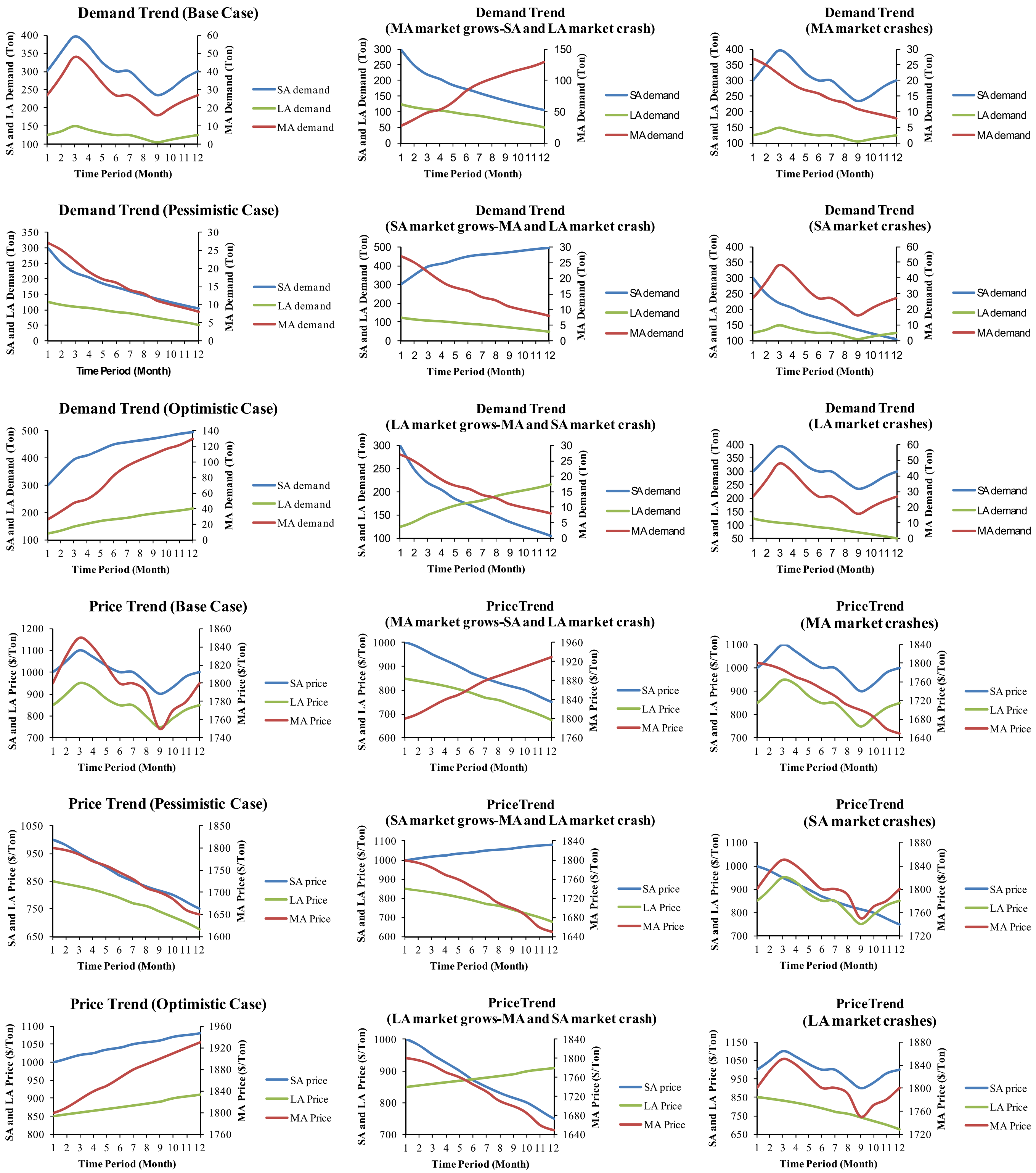

Fig. 7. Market scenarios for the biochemical option.

The steam balance must be satisfied. Enough steam must be produced by boilers and other steam producing equipments to satisfy the needs of other steam consuming processes. However, extra steam may be produced and vented off if not necessary, as represented in Eq. (41).

$$\sum_{\{l,p,r\}\in R^p} (v_{lpt}^{output} - v_{lpt}^{input}) \geq 0 \qquad \forall \{l,p\} \in P^L, t \in T \tag{41}$$

6. Case study

A P&P mill aims at implementing FBR. Two product/process portfolios are considered. In the first portfolio, called Thermo-chemical option, Fischer–Tropsch liquids (FTL) are produced by biomass gasification and a generic gas-to-liquid process, and then are separated into waxes and diesel. Diesel can be converted into jet fuel (JF). The second portfolio, called biochemical option, involves production of succinic acid (SA), malic acid (MA) and lactic acid (LA). All three products are produced in similar fermenters. SA and MA can be recovered in a similar recovery system, but LA needs a specific recovery system.

The process alternatives related to thermochemical option are shown in Fig. 3. All alternatives are similar up to JF production line, as shown at the top of Fig. 3. The rest of the process is shown at the bottom of this figure for each alternative. In the first alternative, A-1, FTL is separated into waxes and diesel. The waxes are sold, and the whole diesel is converted to JF. In the second alternative, A-2, a smaller process is used to convert diesel to JF. Hence, this system would have more potential for flexibility in terms of product. The third alternative is a combination of A-1 and A-2. Two small processes are used in parallel. If both are in operation, it performs like alternative A-1 and if one of them is shut down, it performs like alternative A-2. This alternative has the highest potential for flexibility among others.

For the biochemical option, two process alternatives have been considered (Figs. 4 and 5). In the first alternative, B-1 (Fig. 4), there are two separate lines. The first line produces SA and MA in different production modes and the second line produces LA. In the second alternative, B-2 (Fig. 5), an SA/MA recovery system is added to the LA production line, so that this line can be changed over to produce SA or MA. One of SA/MA and LA recovery systems is always in standby mode. Therefore, second alternative has more potential for flexibility. It must be mentioned that all process alternatives have already been defined through studying the required level of flexibility for each portfolio. For further information, the reader is referred to Mansoornejad et al. (2012).

After defining process alternatives, SC network alternatives must be defined and combined with the process alternatives. The new products are characterized and based on them, type of storage and transportation systems for each of them are identified. More importantly, partnership strategies for each alternative are defined. Tables 1 and 2 show the SC network alternatives defined for the each portfolio option. Company's restrictions and policies must be considered in the definition of the SC network alternatives. Therefore, different processing, selling strategies, transportation and partnership shown in these tables are defined by the mill's executives. Thermochemical option, which has three process alternatives, has six SC network alternatives. Each process alternative is associated with two SC network alternatives. Biochemical option has two process alternatives. Two SC network alternatives are associated with each of them, making four SC network alternatives in total.

The SC networks are defined considering the process options. For process alternative A-1, which can potentially convert the whole diesel into JF, there are two SC network alternatives at the processing stage; either making partnership with a JF producer which in turn implies a specific selling strategy for diesel, i.e. selling diesel completely to JF producer, or producing JF at the mill. For process alternative A-2, which can produce both diesel and JF, there are two SC networks alternatives at the sales level for diesel; either making a contract with a partner and sending diesel to him, or selling it on the spot. For process alternative A-3, there are two SC network alternatives at the transportation level for wax and diesel; either buying trucks, or making contract with a transportation company.

For process alternative B-1 and B-2, SC network alternatives are different at processing level. There are two alternatives; either sending the extractives (hemicelluloses and C5 sugars) to a partner for more processing, or processing them at the mill. Moreover, different transportation strategies can be defined.

The total capital investment required for each combined alternative is shown in Table 3.

Market scenarios for each alternative, representing market volatility, are presented in Figs. 6 and 7.

The definition and justification of each market scenario are presented for the biochemical option in Table 4. The same approach was implemented for defining the market scenarios for the Thermochemical option. Contractual price and demand for each product is fixed over the entire year, while the spot prices and demands are changing throughout the year. In fact, the difference among market scenarios is in terms of spot price and demand, and the contractual prices and demands are the same in all market scenarios.

7. Results and discussion

Base-case profitability, flexibility and robustness of process alternatives (combined alternatives excluding SC network alternatives) are depicted in Fig. 8. The value of flexibility metric shown in this graph is the average flexibility used by each alternative in all scenarios. As shown by the flexibility metric in this figure, as the potential for flexibility increases, more flexibility is used. Moreover, as more flexibility is used, robustness increases, meaning that the SC is more robust against volatility. But profitability does not have the same behaviour as flexibility increases. It is illustrated that alternative A-3, which has the highest potential for flexibility and also more flexibility is used on this alternative, has the lowest profitability. That is due to the fact that profit improvement as a result of higher flexibility cannot compensate the increase in capital cost and the extra capital cost paid for more flexibility is not paid off in this case. The profit acquired by each combined alternative for thermochemical option is presented in Fig. 9. It can be seen that the profits of all alternatives in each market condition are close to each other, though the alternative A-3 with own fleeting has the highest profit.

The results for each combined alternative are presented in this section. Process alternative A-1 has two SC network alternatives at the processing level, one implying sending diesel to a JF producer and one including JF production at the mill. The IRR and robustness of these two combined alternatives are illustrated in Fig. 10. The IRR of the alternative of sending diesel to JF producer is much

Table 4
Market scenarios for the biochemical option.

Scenario	Definition	Justification
Sc.1: Base case	Sinusoidal trend for price and demand of all products	Showing the volatility in the price and demand of products
Sc.2: Pessimistic	Price and demand of all products decline	Testing system's response in a situation in which market is weak
Sc.3: Optimistic	Price and demand of all products increase	Testing system's response in a situation in which market is strong
Sc.4	MA market grows, SA and LA markets crash	Testing system's response when MA market is stronger than SA and LA markets
Sc.5	SA market grows, MA and LA markets crash	Testing system's response when SA market is stronger than MA and LA markets
Sc.6	LA market grows, MA and SA markets crash	Testing system's response when LA market is stronger than MA and SA markets
Sc.7	MA market crashes, SA and LA markets follow the base-case trend	Testing system's response when MA market is weaker than SA and LA markets
Sc.8	SA market crashes, MA and LA markets follow the base-case trend	Testing system's response when SA market is weaker than MA and LA markets
Sc.9	LA market crashes, SA and MA markets follow the base-case trend	Testing system's response when LA market is weaker than SA and MA markets

higher than that of producing JF at the mill. It means that producing JF at the mill, with current price or production cost, is not profitable. Therefore, company may sell its diesel to a JF producer which will also secure company's diesel market. But, it can be seen that the robustness of the alternative of producing JF at the mill is higher. That is because of the increase in flexibility. The system is more flexible when it produces one more product. It gives more flexibility to the company in a volatile market, and thus makes it more robust against market volatility.

Process alternative A-2 has two SC network alternatives at the sales level; sending diesel to a partner or selling it on the spot. Fig. 11 reveals that both alternatives have almost equal IRR, but robustness of sending diesel to a partner is higher. The reason is that in this way the company externalizes the risk of facing with volatility in diesel market by transferring it to the partner.

Process alternative A-3 is associated with two SC network alternatives at the transportation level; buying trucks, i.e. own fleeting, or making contract with a transportation company. Fig. 12 shows that both alternatives have almost equal IRR and robustness. Thus, although from an economic point of view there is no difference between these two alternatives, second alternative implies less risk and responsibility. Instead of buying a network of trucks and taking care of them and their logistics, the company can easily outsource its transportation system and still have the same economic result.

Same results are presented in Figs. 13 and 14 for the biochemical option. It is clear that by increasing flexibility in this alternative, the profit is improved considerably. Fig. 13 reveals that by increasing the potential for flexibility, more flexibility is used. Moreover, with more flexibility, profit (Fig. 14) and robustness (Fig. 13) are enhanced. Contrary to Thermochemical option, profitability also improves as flexibility increases. This means that for the biochemical option, the extra capital cost paid for adding one recovery system for SA/MA to the first production line is very well compensated by the increase in capability of system to produce more profitable products.

The process alternatives of biochemical option have two SC network alternatives at the processing level; either sending the extractives to a partner or processing them at the mill. Unlike the Thermochemical option for which producing JF at the mill is less

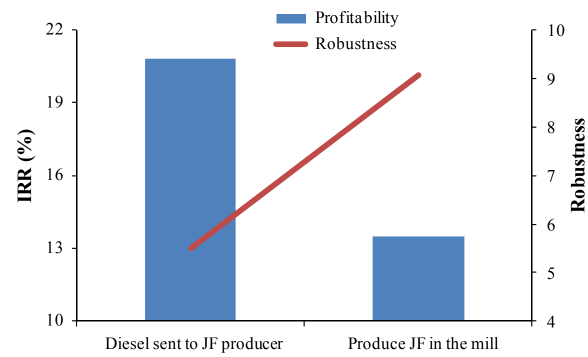

Fig. 10. Profitability and Robustness for SC Alternatives: A-1.

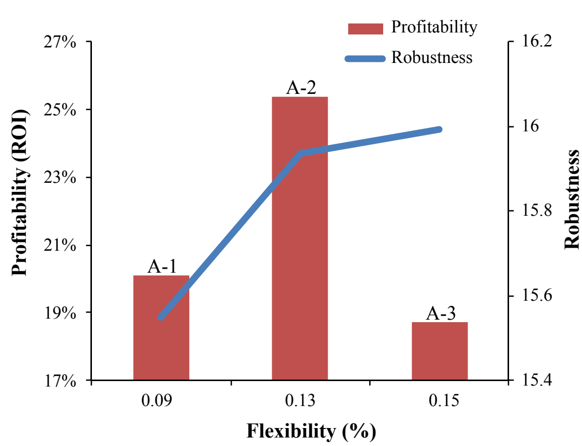

Fig. 8. Robustness and profitability vs. flexibility: Thermochemical option.

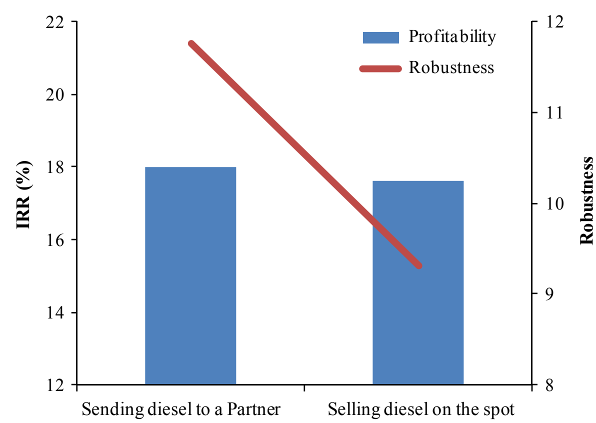

Fig. 11. Profitability and Robustness for SC Alternatives: A-2.

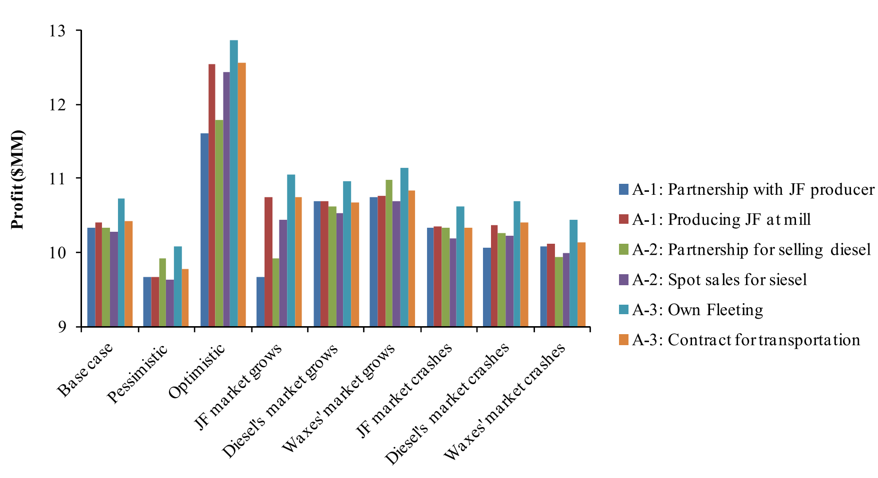

Fig. 9. Profit of combined alternatives for all scenarios: Thermochemical option.

profitable than sending it to a JF producer, for the biochemical option processing the extractives at mill is much more profitable than sending it to a partner, as illustrated in Fig. 15. This is due to the fact that extractives being processed at the mill are used to produce xylitol, which is a very high value product. The results approve that added-value products can significantly increase the profitability of a company compared to commodities. The high profit associated with added-value chemicals helps them internalize the risk of volatility, i.e. the profit may decrease due to market volatility, but remains still high compared to commodities. In addition, robustness of the alternatives which involve processing the extractives at the mill is considerably higher than the robustness of alternatives which include sending the extractives to a partner. This again supports the notion that robustness improves with flexibility. The flexibility of the system is higher in the case the extractives are processed at the mill, because of producing one more product.

An important point to be mentioned is that the design of a process alternative affects the design of SC network alternatives and the strategies of SC management at the operational level. Figs. 16 and 17 illustrate that, in similar market conditions, different patterns of order acceptance is chosen for different levels of flexibility, i.e. for alternative B-1 and alternative B-2, which imply different inventory management, different sales strategies, and different transportation strategies.

When flexibility of processes is increased, production capacity of products will change. In this case, some new opportunities in the market might be found. That will change the strategies of the company, because the new opportunity may imply a specific partnership, sales strategy, new warehouses or new transportation system or transportation strategy. Moreover, a specific level of flexibility requires a specific inventory limit and transportation capacity. These are SC network design issues that are linked to and affected by the process considerations. This implies that designing the SC network consistent with process flexibility is very important. There is a direct relationship between level of flexibility, and the configuration and specifications of the SC network, and thus, it is worth integrating them.

In conclusion, it can be said that the biochemical option is much more profitable than the thermochemical option. The potential for flexibility in the biochemical option is used better compared to the thermochemical option and thus it is more robust against market volatility. For the thermochemical option, partnership in all levels makes the project more profitable, while for the biochemical option, partnership at the processing level reduces

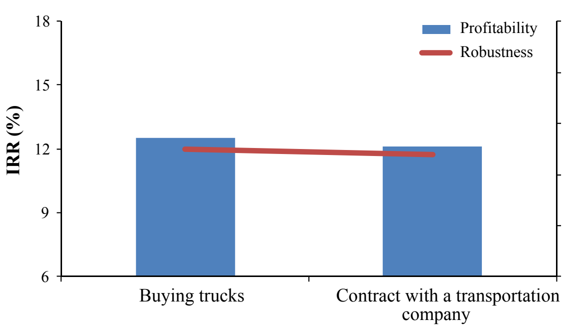

Fig. 12. Profitability and Robustness for SC Alternatives: A-3.

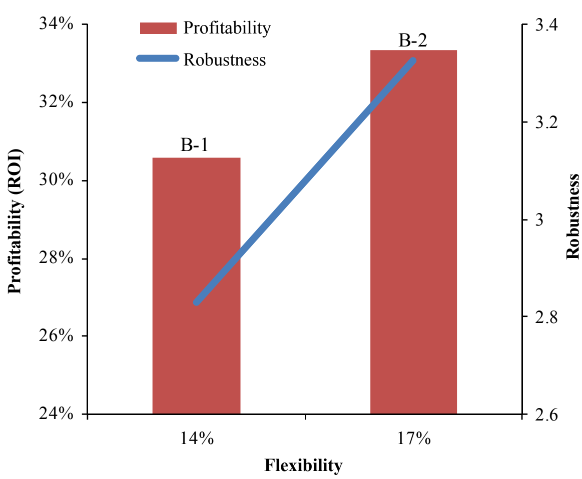

Fig. 13. Robustness and profitability vs. flexibility: biochemical option.

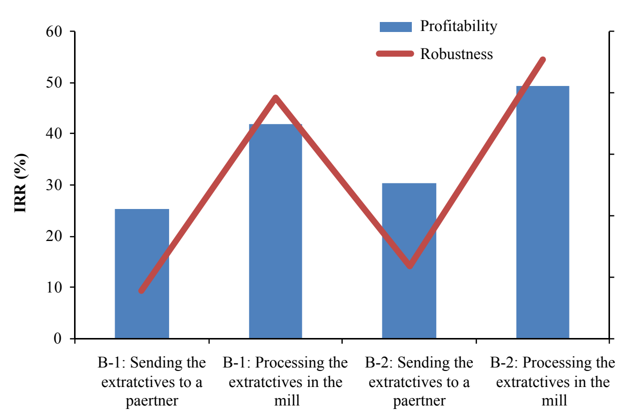

Fig. 15. Profitability and Robustness for SC Alternatives: biochemical option.

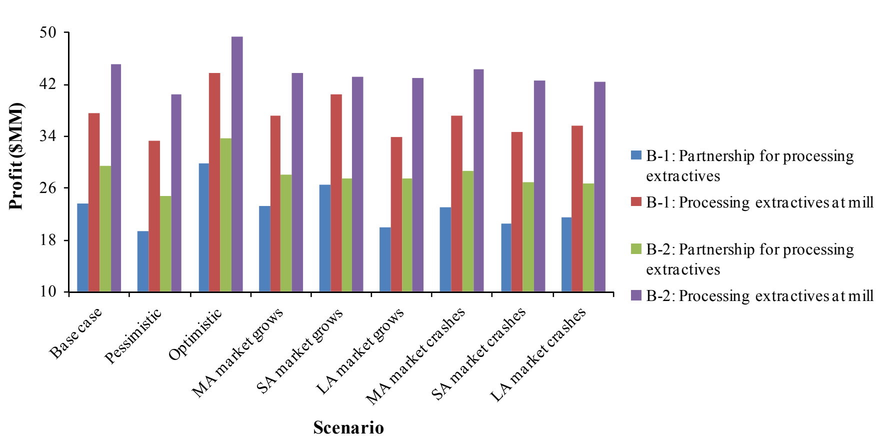

Fig. 14. Profit of combined alternatives for all scenarios: biochemical option.

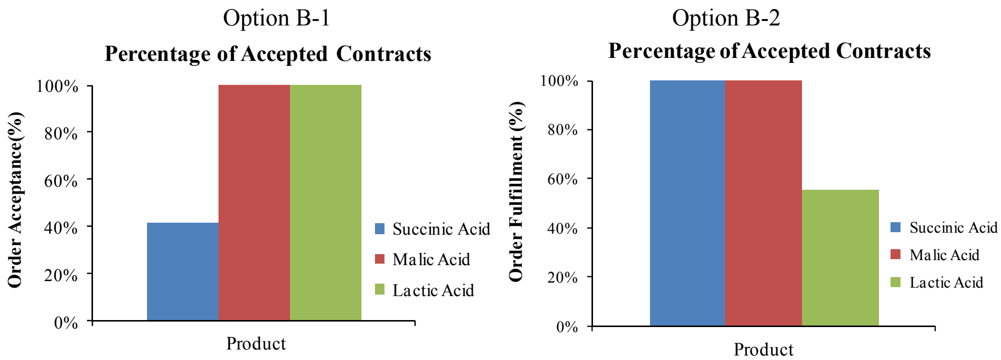

Fig. 16. Percentage of accepted contracts: biochemical options.

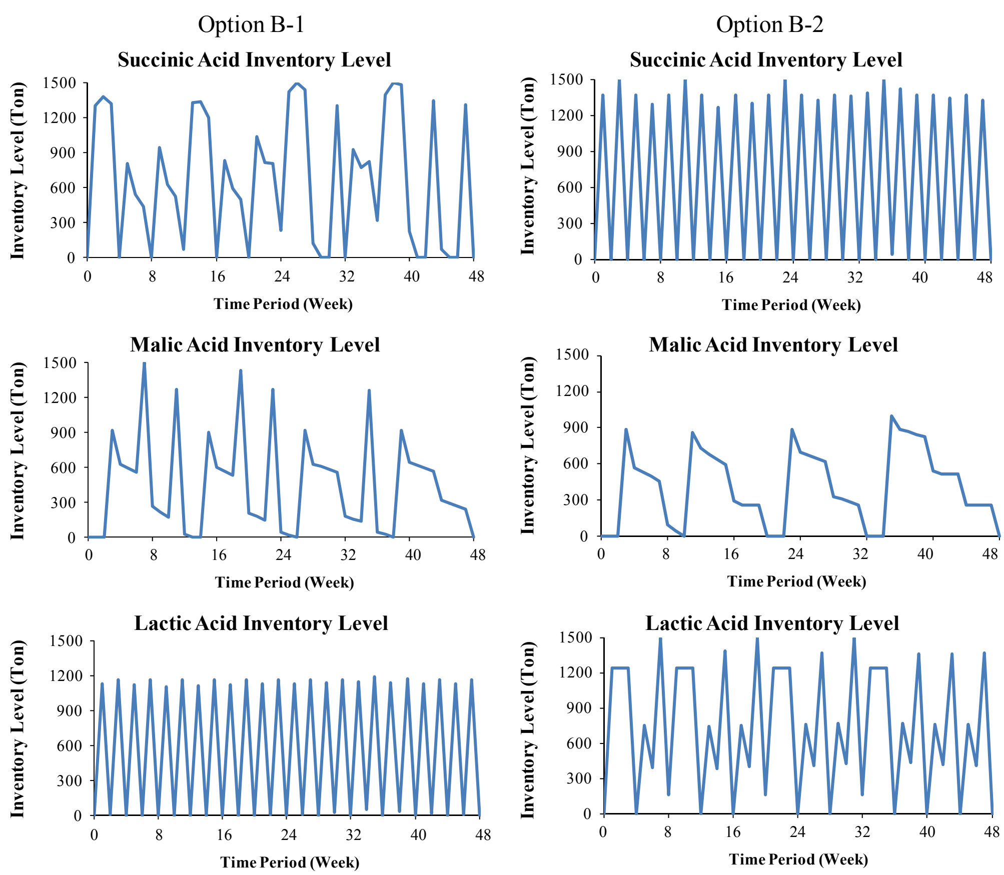

Fig. 17. Inventory levels: biochemical options.

the profitability of the project. Other factors in this regard come to the table such as access to capital for implementing the project. Partnership in other levels such as transportation and sales might make the project more profitable. The defined product portfolio option must be analyzed by other tools, e.g. LCA, so that other aspects of implementing such projects are revealed. Ultimately, an MCDM framework can takes into account all different aspects for making the final decision.

8. Conclusions

In the real world, forestry companies face limited options in terms of future strategies, product/process options, access to biomass, product market, etc. These all limit the choice of a company for its future. Therefore, instead of using large-scale SC mathematical formulations which consider thousands of options, a practical scenario-based approach can be used to identify the possible options and evaluate their performance in the long run. Biorefinery alternatives involving product portfolio, process alternatives and SC network configurations considered by a company willing to implement the biorefinery, can be evaluated using the scenario-based methodology proposed in this paper. By comparing the profitability of alternatives as well as their robustness in volatile market conditions, and by screening out the non-profitable ones, a set of biorefinery alternatives to be considered can be identified.

Furthermore, it was shown by the results that a specific level of flexibility affects the strategies in sales, partnership and transportation. With the proposed approach, i.e. defining SC alternatives related to process alternatives, the following aspects can be addressed relative to process alternatives:

- As a result of change in level of flexibility and thus, change in production capacity, the procurement, transportation, and selling costs and strategies will be different. Only a SC analysis can takes into account all these changes.

- The inventory levels and storage capacity will also be different for different levels of flexibility. Again, a SC analysis can calculate the inventory level of each product according to the production scheme and determine the storage capacity required for each product.

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