Strategic redesign of the forest-based biomass supply chain through optimization and sensitivity analysis

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Abstract. The Forest Biorefinery Supply Chain (FBSC) redesign problem is addressed. A Generalized Disjunctive Programming (GDP) model is constructed and it is reformulated as Mixed Integer Linear Programming (MILP). The proposed superstructure of FBSC scope (i) the strategic location of forest biomass-based biofuel facilities, and its integration with installed traditional forest industries. In addition, the model determine (ii) feedstock harvesting amount at each forest area; and (iii) transportation flows along all FBSC arcs over a multi-period horizon planning. The applicability of the proposed model is demonstrated through a case study considering different uncertainty settings. A series of sensitivity analyses is performed to determine the impact of variations on the proposed FBSC. The variations in the selling price of products, biomass availability, and demand of products are addressed in the sensitivity analysis.

Keywords: Supply Chain Redesign, Forest Biorefinery, Sensitivity Analyses.

1 Introduction

Production of bioenergy and biofuels from forest-based biomass provides an economically and environmentally attractive use of an otherwise wasted material [1]. In Argentina, there are thousands of sawmills and several pulp and/or paper companies mainly concentered in northeastern region of the country. These facilities produce million cubic meters of industrial biomass like sawdust and kraft black liquor. Also harvesting activities generate a significant amount of residues. However, the use of all these biomass is low, more than 70% is unused [2], and most of the harvest residues are burned, and missing out the opportunity of producing either biofuels or other products of higher value.

Through various conversion technologies, the aforementioned forest-based biomass can be converted into a variety of bioenergy (e.g., heat and power) and biofuel types (e.g., solid, liquid, and gaseous) [3]. In several countries with extensive forest industries, efforts are currently underway to develop drop-in biofuels from lignocellulosic forest residue-based feedstocks [4]. In this context, the integration of biorefineries with the traditional forest industries has emerged as a sustainable alternative to improve the competitiveness of the sector. This work addresses the optimal redesign of the "Forest Biorefinery Supply Chain" (FBSC), specifically, we extend a previous work [5] (in which the FBSC design problem is addressed) to solve the redesign and multi-period planning of the FBSC. The model proposed in this paper is a multi-period linear GDP, re-formulated as a MILP. Due to the exogenous uncertainty in several parameters, a set of scenarios are developed for sensitivity analysis considering simultaneous changes in: (*i*) biofuel selling price, (*ii*) final products (e.g., kraft pulp and biodiesel) demand, and (*iii*) discounts for the integration of plants in the same node. Thus, the aim of the present study is to analyze the impact of these fluctuations on the model outputs factors.

2 Problem statement

A three-layer FBSC superstructure has been utilized, which includes the forest areas, processing facilities nodes, and consumer regions (see Fig. 1). The addressed FBSC decision problem can be described as follows:

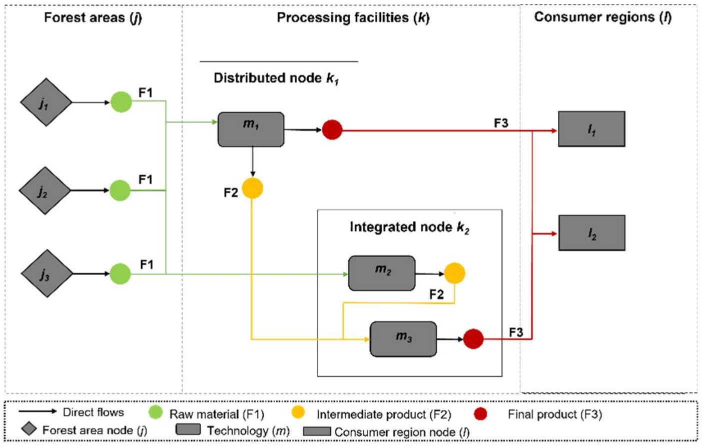

Fig. 1. An illustrative instance of a generic FBSC

Given: (*i*) the county-level available land, (*ii*) biomass yield at each site, (*iii*) candidate biorefinery locations, (*iv*) fixed location of traditional forest industries, (*v*) potential biofuel conversion technologies, and (*vi*) yields for each product and technology, capital cost at baseline capacity, and unit production costs, (*vii*) transportation costs for each raw material, intermediate, and final product type, and (*viii*) discounts when co-location is decided; The *goal* is to determine, for each time period: (*i*) the number, technology, location, and scale of each biorefinery, (*ii*) the capacity profiles at all SC processing facilities, (*iii*) the transportation flows along all SC arcs, (*iv*) the production levels at each processing pathway, and (v) superficies of land and specific tree species to harvest. The objective function is the maximization of the net present value.

3 Model formulation

Given the supply chain superstructure presented in Fig. 1, the GDP model is formulated accordingly. Lowercase italic Greek letters are used for parameters, uppercase bold Greek letters for Boolean variables, and uppercase Latin letters for non-negative variables. The GDP formulation is given by Eqs. (1)–(15).

$$\begin{aligned} Max\ \mathbf{NPV} = \sum_t \frac{1}{(1+\varpi)^{t-1}} \Bigg(& \sum_{o,m} \lambda_o \cdot F_{o,m,t}^{k,l,p} - \sum_{j,s} ICJ_{j,s,t} - \sum_{m,c,k} ICK_{k,m,c,t}^{exp} \\ & - \sum_{k,m,c} FCK_{k,m,c,t} - \sum_{m,r,s,j,k} \theta_r \cdot F_{r,s,m,t}^{j,k,c} - \sum_{m,r,s,j,k} \theta_m^{r,s} \cdot F_{r,s,m,t}^{j,k,c} \\ & - \sum_{i,m,c,\hat{k},\hat{m},\hat{c}} \theta_m^i \cdot \mathrm{F}_{i,\hat{k},\hat{m},\hat{c}}^{k,m,c,t} \\ & - \sum_{j,k,r,s,p,m} \tau_{j,k,r}^{var} \cdot F_{r,s,m,t}^{j,k,c} - \sum_{i,m,c,\hat{k},\hat{m},\hat{c}} \tau_{i,k,\hat{k}}^{var} \cdot \mathrm{F}_{i,\hat{k},\hat{m},\hat{c}}^{k,m,c,t} \\ & - \sum_{k,l,o,p,m} \tau_{o,k,l}^{var} \cdot F_{o,m,t}^{k,l,p} \Bigg) \end{aligned} \tag{1}$$

The objective function considered is to maximize Net Present value given by Eq. (1) which includes incomes, transportation costs, fixed costs, variable operating costs, and capital costs.

$$\begin{bmatrix} \boldsymbol{\Lambda}_{j,s,t} \\ ICAP_{j,r,s,t} = \gamma_{j,s,t} \cdot \alpha_{r,s} \ \ \forall r \\ ICJ_{j,s,t} = \gamma_{j,s,t} \cdot \beta_{j,s} \end{bmatrix} \underline{\vee} \begin{bmatrix} \neg\boldsymbol{\Lambda}_{j,s,t} \\ ICAP_{j,r,s,t} = 0 \ \ \forall r \\ ICJ_{j,s,t} = 0 \end{bmatrix} \ \forall\ j,s,t \tag{2}$$

Eq. (2) presents a yes-no disjunction, where Boolean variable $\boldsymbol{\Lambda}_{j,s,t}$ is introduced to decide if the area of tree species s available in the forest node j from period t is used. In the positive case, the first equation defines the capacity of raw material r from tree species s ($ICAP_{j,r,s,t}$). The following equation establishes the capital cost to make use of tree species s in forest area location j from period t ($ICJ_{j,s,t}$). In the negative case ($\neg\boldsymbol{\Lambda}_{j,s,t}$), investment is not decided, then no capital cost is generated and no capacity of raw material r from tree species s is assigned to node j in period t.

$$\begin{bmatrix} \boldsymbol{\Phi}_{k,m,c} \\ NP_{k,m,c} = 1 \\ GCAP_{k,m,c} = \delta_m \cdot \varepsilon_c \\ \begin{matrix} \boldsymbol{\Psi}_{k,m,c,t} & & \neg\boldsymbol{\Psi}_{k,m,c,t} \\ \begin{bmatrix} ICK_{k,m,c,t}^{exp} = ACAP_{k,m,c,t}^{exp} \cdot \beta_{m,c} \\ FCK_{k,m,c,t}^{exp} = ACAP_{k,p,m,c,t}^{exp} \cdot \gamma_{m,c,p} \\ ACAP_{k,m,c,t}^{exp} \geq \kappa_{m,c} \cdot GCAP_{k,m,c} \end{bmatrix} & \underline{\vee} & \begin{bmatrix} ICK_{k,m,c,t}^{exp} = 0 \\ FCK_{k,m,c,t}^{exp} = 0 \\ ACAP_{k,m,c,t}^{exp} = 0 \end{bmatrix} \forall\ t \end{matrix} \end{bmatrix} \underline{\vee} \begin{matrix} \neg\boldsymbol{\Phi}_{k,m,c} \\ \begin{bmatrix} NP_{k,m,c} = 0 \\ GCAP_{k,m,c} = 0 \end{bmatrix} \end{matrix} \forall\ k,c,\mathrm{m} \tag{3}$$

The first decision level of nested disjunction (3), determines if technology m with capacity level c is located at node k by Boolean variable $\boldsymbol{\Phi}_{k,m,c}$. If this Boolean variable is true, the investment is decided. In the first equation, an auxiliar variable $NP_{k,m,c}$ is introduced for counting conversion path m installed at location k with capacity level c. Then the second equation of this disjunction determines the global processing capacity, represented by variable $GCAP_{k,m,c}$. The following nested decision level define the dynamic capacity profile of each facility. The capital cost for expansion is represented in the first equation of this disjunction by variable $ICK^{exp}_{k,m,c,t}$, while the capacity expansion ($ACAP^{exp}_{k,m,c,t}$) is low bounded in the second equation of the disjunction.

$$\begin{bmatrix} \boldsymbol{\Omega_{k,m,c,t}} \\ FCK_{k,m,c,t} \geq \sum_{t' \leq t} FCK^{exp}_{k,m,c,t'} \\ \mu_{m,c} \cdot ACAP_{k,m,c,t} \leq \sum_{j,(r,s)\in M_{RS}} F^{j,k,p}_{r,s,m,t} + \sum_{i\in M_I,\hat{k},\hat{m}\in I_M} F^{k,m,\hat{k},\hat{m}}_{i,p,t} \leq ACAP_{k,m,c,t} \end{bmatrix} \tag{4}$$

$$\underline{\vee} \begin{bmatrix} \neg\boldsymbol{\Omega_{k,m,c,t}} \\ FCK_{k,m,c,t} \geq \sum_{t' < t} FCK^{exp}_{k,m,c,t'} \\ \sum_{j,(r,s)\in M_{RS}} F^{j,k,p}_{r,s,m,t} + \sum_{i\in M_I,\hat{k},\hat{m}\in I_M} F^{k,m,\hat{k},\hat{m}}_{i,p,t} = 0 \end{bmatrix} \forall\, k, c, \mathrm{m}, \mathrm{t}$$

Disjunction (4) determines whether technology m with capacity level c located at node k is in operation at time t ($\boldsymbol{\Omega_{k,m,c,t}}$). The first equation of Eq. (4) establishes the annual fixed cost, as a result of succession of expansions, previously defined in disjunction (3). Meanwhile, the second equation establishes that the input flow must satisfy lower and upper bounds of use of the annual installed capacity ($ACAP_{k,m,c,t}$). Note that the input flow could be raw material, $F^{j,k,p}_{r,s,m,t}$, or intermediate products coming from other plants, $F^{k,m,\hat{k},\hat{m}}_{i,p,t}$. If the plant does not operate, the corresponding input flow is zero. However, even if the facility does not operate, the annual fixed cost must be considered.

$$\underset{n}{\underline{\vee}} \begin{bmatrix} \boldsymbol{\Upsilon^{int}_{k,n}} \\ \sum_m \sum_c NP_{k,m,c} = \xi_n - 1 \\ ICK^{int}_{k,t} = (1 - \pi 1_n) \cdot \sum_m \sum_c ICK^{exp}_{k,m,c,t}\ \forall\, t \\ FCK^{int}_{k,t} = (1 - \pi 2_n) \cdot \sum_m \sum_c FCK_{k,m,c,t}\ \forall\, t \end{bmatrix} \forall\, k \tag{5}$$

Equation (5) presents a disjunction of n terms for integrated node configuration for all locations k. Boolean variable $\boldsymbol{\Upsilon^{int}_{k,n}}$ is introduced to decide the co-location of n facilities at the same processing node k. The first equation establishes the number of plants installed at site k, this is represented by auxiliar variable $NP_{k,m,c}$ previously introduced in Eq. (3). The capital cost for co-location of biofuel technology represented by variable $ICK^{int}_{k,t}$ is calculated in the second equation of disjunction (5), where $\pi 1_n$ is the discount parameter. The same approach is assumed for the fixed operating cost, fixed cost is represented by variable ($FCK^{int}_{k,t}$) in the third equation of disjunction (5) and parameter $\pi 2_n$ is the discount to apply.

$$VCAP_{j,r,s,t} = ICAP_{j,r,s,t} \qquad \forall\, j,r,s,t = 1 \qquad (6)$$

$$VCAP_{j,r,s,t} = VCAP_{j,r,s,t-1} + ICAP_{j,r,s,t} - \sum_{k,c,m \in M_{RS}} F^{j,k,c}_{r,s,m,t-1} \qquad \forall\, j,r,s,t > 1 \qquad (7)$$

$$ACAP_{k,m,c,t} = ACAP^{exp}_{k,m,c,t} \qquad \forall\, k,c,m,t = 1 \qquad (8)$$

$$ACAP_{k,m,c,t} = ACAP_{k,m,c,t-1} + ACAP^{exp}_{k,m,c,t} \qquad \forall\, k,c,m,t > 1 \qquad (9)$$

$$\sum_{t} ACAP^{exp}_{k,m,c,t} = GCAP_{k,m,c} \qquad \forall\, k,c,m \qquad (10)$$

Eqs. (6-7) establish the feedstock capacity for periods $t = 1$ and t greater than 1, respectively Eqs. (8) and (9) establish the annual processing capacity of each processing facility, while Eq. (10) ensures that the sum of the capacities expanded in each period t must be equal to the installed global capacity ($GCAP_{k,m,c}$).

$$\sum_{l} F^{k,l,c}_{o,m,t} = \sum_{(r,s) \in M_{RS}} \sigma^{r,s,o}_{m} \cdot \sum_{j} F^{j,k,c}_{r,s,m,t} + \sum_{i \in M_I} \sigma^{i,o}_{m} \cdot \sum_{(\hat{k},\widehat{m},\hat{c}) \in I_M} \mathrm{F}^{\hat{k},\widehat{m},\hat{c},t}_{i,k,m,c,} \quad \forall\, k,(m,o) \in M_O, c, t \qquad (11)$$

$$\sum_{(\hat{k},\widehat{m},\hat{c}) \in M_I} \mathrm{F}^{k,m,c,t}_{i,\hat{k},\widehat{m},\hat{c}} = \sum_{(r,s) \in M_{RS}} \sigma^{r,s,i}_{m} \cdot \sum_{j} F^{j,k,c}_{r,s,m,t} \qquad \forall\, k,(m,i) \in I_M, c, t \qquad (12)$$

The mass balance at processing nodes k are represented by constraints (11)– (12). Eq. (11) indicates the amount of final product o sent to all consumption nodes l (left side), must be equal to the produced amount obtained from raw material r of specie s (first term of the right side) and/or from intermediate product i (second term of the right side). In the same way, Eq. (12) indicates that the production of intermediate product i using raw materials r of tree species s (right side) is equal to the amount of intermediate product i shipment from node k supplied to all nodes $\hat{k}$ with conversion technology $\widehat{m}$ in time period t (left side). Note that several restrictive multidimensional sets are established to define technologies that consumes raw materials (M_{RS}), technologies that consumes intermediate products (M_I), technologies that produces intermediate product (I_M), and technologies that generates final product (M_O).

$$\sum_{k,m \in M_O} F^{k,l,p}_{o,m,t} \geq \chi_{l,o,t} \qquad \forall\, t,(o,l) \in OL \qquad (13)$$

Eq. (13) ensures the satisfaction of the demand ($\chi_{l,o,t}$) for all types of final product o in the different markets l for the different periods t. Finally, logic relations are modeled, as can be seen in Eq. (14)-(18).

$$\sum_{c} \boldsymbol{\Phi}_{k,m,c} \leq \mathbf{1} \qquad \forall k,m \qquad (14)$$

$$\boldsymbol{\Phi}_{k,m,c} \geq \boldsymbol{\Omega}_{k,m,c,\mathrm{t}} \qquad \forall k,m,c,t \qquad (16)$$

$$\boldsymbol{\Omega}_{k,m,c,\mathrm{t}} \geq \boldsymbol{\Psi}_{k,m,c,\hat{\mathrm{t}}} \qquad \forall k,m,c,t,\hat{\mathrm{t}}, t\hat{\ } \leq t \qquad (17)$$

$$\sum_{\hat{\mathrm{t}} \leq t} \boldsymbol{\Psi}_{k,m,c,\hat{\mathrm{t}}} \geq \boldsymbol{\Omega}_{k,m,c,\mathrm{t}} \qquad \forall k,m,c,t,\hat{\mathrm{t}} \qquad (18)$$

4 Case Study

This section presents a case study with the aims of illustrating the capabilities of the proposed model. Most of the input data is similar to that in [5]. The geographical scope of the case study is limited to the north-western and centre region of Argentina where the most forest biomass production is found. The potential locations for biofuel facilities are based on the geographical zones defined by the national census of sawmills in Argentina [6]. Therefore, the aforementioned geographical zones are considered as potential facility nodes where its centroid is the possible location of the processing facility. The number of the potential processing plants considered in this case study are 9 biofuel plants. It is assumed that the sawmills are located in the 9 defined nodes, and kraft pulp mills are located in other defined nodes. The demand nodes are classified into two categories: cellulosic pulp consumer regions and oil refineries. In this case study, kraft pulp, bioethanol, and biodiesel are considered as final products. Kraft pulp consumer regions are the regions which concentrate the country's paper industrial activity, while bio-oils consumer regions are representative oil refineries existing in the north of Buenos Aires. The biofuel demands are estimated based on consumption of oil refineries between years 2012 and 2018.

4.1 Biofuel and kraft pulping production technologies

Reference techno-economic input parameters have been estimated considering previous literature references, experts and stakeholders reports and surveys. For the production of biofuels, three technologies are considered in this work (see Table 1). The pulp factories referred in this work represent standard market pulp and paper mills. Here, it is assumed that the biofuels conversion technologies have the necessary flexibility to process the different residues considered in this work.

Table 1. Techno-economic input data for each conversion pathway in this study

Technology	Yield	Capital cost	Fixed cost	Variable cost	Base capacity	Source
	$[T_{out}\ T_{input}^{-1}]$	[USD Ty^{-1}]	[USD Ty^{-1}]	[USD T^{-1}]	$[1000T_{input}y^{-1}]$	
HTL	0.44 0.32	486	19	26	666	[7]
CFB-FT	0.216	760	21	46	672	[8]
SP-SSF	0.17 0.23	1026	41	18	200	[9]
Kraft	0.5 0.5	1500	60	68.25	900	[10]

HTL Hydrothermal liquefaction, CFB Circulating fluidized bed, FT Fischer-Tropsch synthesis, SP Steam Explosion Pretreatment, SSF Simultaneous saccharification and fermentation

5 Results

The solution for the proposed deterministic model is valid and optimal under the deterministic assumption but may not be feasible in case input parameters vary. Then, in order to analyze the performance of the deterministic model under uncertainties, in this section a sensitivity analysis assessment is developed. Specifically, the sensitivity analysis is performed for three types of input parameters: final products selling price (λ_o), final products demand ($\chi_{l,o,t}$), and area available per forest node ($\gamma_{j,s,t}$). The optimization models in this study are run using the GAMS 24.7.4 software and are solved using CPLEX 12.6.3.0 solver on an Intel ® core TM i9-11900K CPU @ 3.50 GHz processor with 32.0 GB RAM.

5.1 Local sensitivity analysis

To perform the local sensitivity analysis (*LSA*), one parameter at a time is varied when others are fixed at their nominal values (i.e., values that are input to the deterministic model). The results of the *LSA* are presented in Table 2. The final products selling price is the most influential parameter of the problem as a 30% decrease in this parameter leads to a 53.7% reduction in net present value. Final products demand is the next important parameter type. Third, biomass availability impacts the net present value directly. Due to high utilization of forest harvest residues for biofuels production, any decrease in the forest area available makes the solution infeasible. Meanwhile, increase in the forest area available have a negligible significance in the objective function.

Fig. 2 gives an overview of the number of located facilities and global installed capacities for each scenario. Changes in the considered parameters have a null impact in installed capacity of biodiesel facilities that are located for all scenarios, while the number and size of bioethanol plants are sensitive to the variation in the aforementioned uncertainty parameters.

Table 2. Local sensitivity analysis results

Parameters	Scenario (% variation of nominal value)	% Change in NPV (Regarding deterministic solution)
Forest area	S1 (30% Decrease)	Infeasible
	S2 (30% Increase)	0.22%
Products demand	S3 (30% Decrease)	-38.91%
	S4 (30% Increase)	29.64%
Selling price	S5 (30% Decrease)	-53.72%
	S6 (30% Increase)	57.21%

As can be seen Fig. 2, bioethanol production is highly sensitive to negative variations of the parameters under fluctuation (see scenarios *S1*, *S3* and *S5*). On the other hand, for scenarios *S2*, *S4* and *S6* the FBCS structure shows the installation of bioethanol plants with higher capacity levels which indicates savings in investment costs as a result of better utilization of benefits of economies of scale. In addition, in scenario *S6* a larger portion of biofuels demand is met, and more processing facilities are opened.

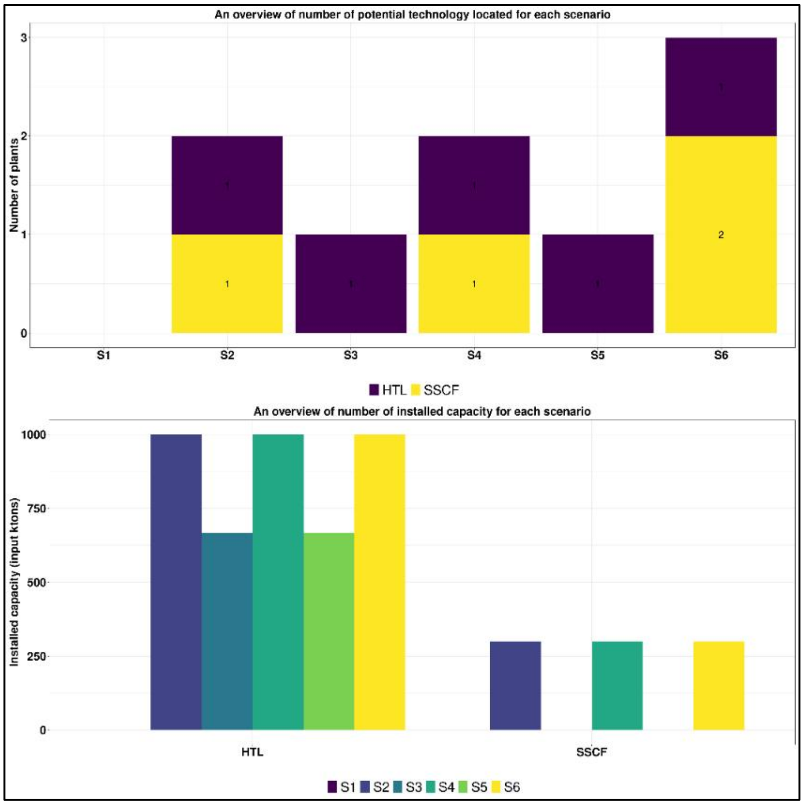

Fig. 2. An overview of number of potential technologies located and installed capacity for each scenario

5.2 Global sensitivity analysis

In order to analyze the impact of fluctuating parameters simultaneously, a global sensitivity analysis (*GSA*) is conducted when all parameters vary at the same time. The aim is to find the parameters that the objective function is most sensitive to. Then, multiple scenarios are generated, assuming that the parameters are uniformly distributed within specified standard deviation from their nominal value. Thus, 100 instances of the original model are run (i.e., 100 iterations are executed and in each one the variation with respect to the nominal value is randomly generated considering a uniform distribution). Table 2 summarizes the main outcomes of the *GSA* and optimal solution of the deterministic model. All of scenarios resulted in optimal solution.

The net present value of 100 instances of the problem is presented in Fig. 3. It shows 16 quadrants as a result of the definition of variation intervals for the sale price and the demand for products and the forest area availability. According to Fig. 3, most of the worst iterations (orange points) where the net present value is less than or equal to the value of the deterministic solution (dashed blue line), are concentrated in the quadrants where the sale price is less than its nominal value. Note that only 8% of these instances have an NPV greater than the value of the deterministic model result. On the contrary, the better iterations (blue points) that have the highest values of the objective function are concentrated in the most optimistic intervals, that is, those where the sale price and the demand increase by at least 15% with respect to their nominal value.

Table 2. Summary and comparison of GSA and deterministic solution outcomes

Output	**Deterministic model**	***GSA* results over feasible runs**		
		Minimum	**Mean**	**Maximum**
Present production cost	595	411	573	721
Present transportation cost	174	121	168	212
Present capital cost	582	314	514	824
Present fixed operating costs	357	327	354	406
Income	3681	1936	3362	5646
Net present value	1973	607	1753	3529

Unlike expected, in the worst scenarios have a feasible behavior from the economic point of view, that is, those scenarios where the sale price and demand decrease by at least 15% with respect to its nominal value have a positive NPV. Note that in these scenarios they do not strictly use the lower limit of variation in the forest area, as it is used in the scenario S1 (infeasible solution, see Table 1) of the local sensitivity analysis.

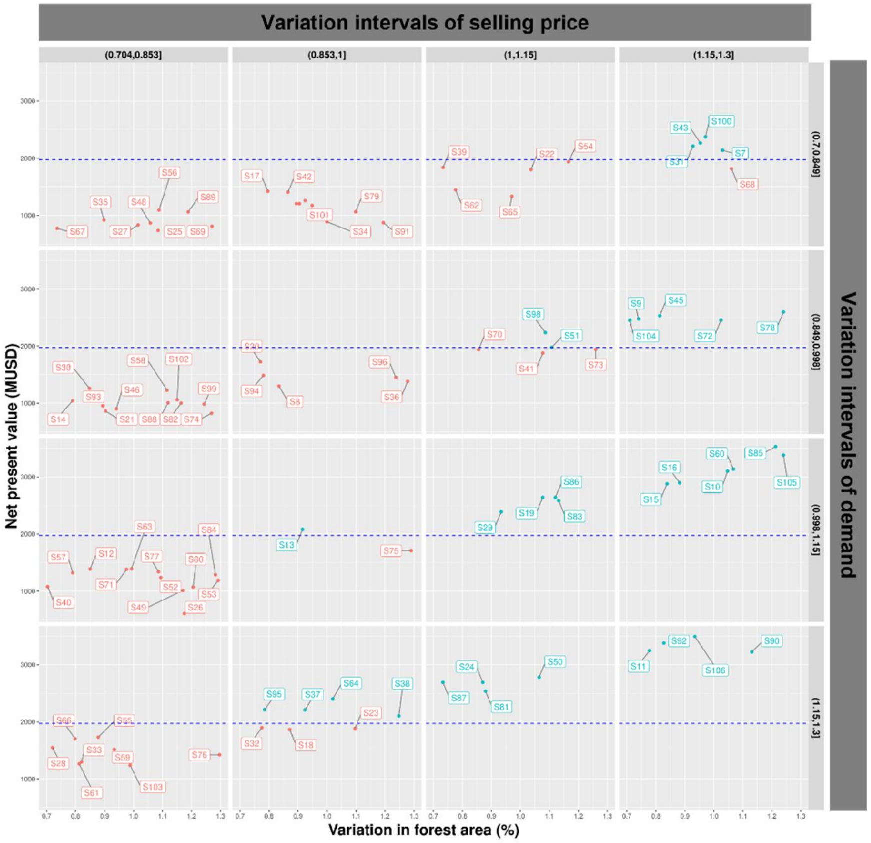

Fig. 3. Net present value of each scenario.

Conclusions

In this article, a multi-period GDP model is developed in order to propose a strategic redesign of the forest bio-refinery supply chain where the integration of the production of biofuels with the traditional forest industries is considered.

According to the results of the local and global sensitivity analyses, selling price, and demand were the most important and impactful parameters. The results of all analyses indicated a high chance of infeasibility in case of the available forest area decrease 30%. Although helpful, neither local and global sensitivity analyses a single solution that was optimum and feasible for all the variations in parameters. Future work includes extending the proposed model using robust optimization.

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