OPTIMAL DESIGN AND PLANNING OF BIODIESEL SUPPLY CHAIN WITH LAND COMPETITION

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Abstract

In this work we propose an MILP multiperiod formulation for the optimal design and planning of the Argentinean biodiesel supply chain, considering soybean, sunflower and jatropha as raw materials. The country has been divided into twenty three regions, corresponding to its provinces, each one including existing crops, oil and biodiesel plants and potential ones, associated to binary variables. The model takes into account intermediate and final products, including seed, flour, pellets and expellers, oil, pure and blending biodiesel and glycerol, together with crop fields, storage and production plants, as well as distribution centers for internal and external markets. The possibility of employing increasing portions of marginal areas for jatropha production has been introduced, as well as this raw material increasing yield along its life cycle. The optimization of this complex network allows simultaneously fulfilling domestic demand of flour, oil and biodiesel while satisfying increasing demands in external markets. The time horizon is of seven years (2012-2018), divided into 84 periods. Numerical results provide insights on the sustainable development of traditional and alternative raw materials and technologies. The mathematical model has been implemented in GAMS providing a complete decision tool that can be applied to other regions or countries by adjusting specific data.

Keywords

Supply Chain, Biodiesel, MILP, Optimal planning, Jatropha

Introduction

Biodiesel production is been explored throughout the world to ensure economical and environmental profits in replacing increasing percentages of fossil based diesel by biodiesel. In order to produce its own biodiesel, each country needs analyzing the economical and environmental feasibility of the complete production chain, beginning from the availability of raw materials, their transformation in intermediate and final products and the storing and distribution of these one to internal and external markets. The result is a great network combining several stages with different options in each stage from alternative biomass crops to the location of product storage and conversion facilities, modes of transportation and flows of biomass and products between regions and abroad.

Supply chain (SC) analysis and optimization have been extensively reported in the literature applied to different process industries (Papageorgiou et al., 2001; Shapiro, 2004; Shah, 2005; Schulz et al. , 2005; Guillen-Gosálbez and Grossmann, 2010; Guillen-Gosálbez et al., 2009, 2010; You and Grossmann, 2007, 2010; Dunnett et al., 2008; Terrazas-Moreno et al., 2010). However, biofuel production is mainly focused on individual aspects of supply chain, as plantation or transportation and there are only a few papers that address the entire biofuel supply chain analysis and optimization. Dunnett et al. (2008) analyze bioethanol SC from lignocellulosic biomass feedstocks. A spatially explicit model combining production and logistics data for United Kingdom is optimized using a profit maximization objective function. The production of bioethanol from lignocellulosic biomass has been also considered by Slade et al. (2009), but in this case, mainly focused on investigating the commercial viability in Europe. More recently, Akgul et al. (2011) propose mixed integer linear programming (MILP) models

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*To whom all correspondence should be addressed to optimize the complete corn-based bioethanol supply chain applied on a case study in Northern Italy. A multi-objective model for sugar/ethanol supply chain optimization is reported by Mele et al. (2011). In this work the authors simultaneously minimize costs and environmental impact at each stage of the production chain. The problem design is formulated as a generic three-echelon supply chain (production-storage-markets) and it is performed on a case study of the sugarcane industry in Argentina. The authors analyze ethanol supply chain including the purchase of sugarcane as raw material, production, storage, transportation and distribution of final products.

Current regulations in Argentina require blends of 5% ethanol in gasoline (Biofuels Law 26093, 2006) and 10% biodiesel blends in gasoil. Current biodiesel production in the country is mainly based in soybean oil, but the production capacity of the country widely overcomes its internal demand. Argentina is the world's third largest soybean producer and global leader as soybean oil supplier (World Oil, 2010). Also, it has the lowest world production cost of soybean and has one of the most efficient oil-crushing industries in the world; its crushing capacity is of around 60 million ton/year, and its exports are over 90% -close to 7.5 million tons- of its annual oil production (SAGPyA, 2010). With a surface area of 3,761,274 km^2, costs related to product distribution for conversion and commercialization can be significantly reduced by the development of biodiesel SC models.

The present work addresses optimal design and planning of the biodiesel supply chain in Argentina from traditional and alternative raw materials, taking into account land competition for seed production, to intermediate and final product sales.

1. Problem Statement

The biodiesel supply chain optimization problem based on agricultural biomass feedstock has been considered as a multiechelon network including alternative locations and capacities for farms, biomass storage sites, crushing plants, oil and byproducts storage, biodiesel production plants, biodiesel storage facilities and distribution centers to internal and external markets.

The country is divided into twenty three regions (provinces) with different biomass yield, production and transportation costs. Soybean, sunflower and jatropha are considered as raw materials, having into account land competition of soybean and sunflower crops. The main feature of jatropha crops is their capacity to grow in marginal areas with extreme climatic conditions. The biodiesel SC model includes mills and biodiesel plants, and storage facilities for intermediate and final products (seeds, flour, pellets and expellers, oils, biodiesel and glycerol). Material flows between regions and to other countries are associated with transportation links. The MILP model optimization was implemented in GAMS maximizing the Net Present Value (*NPV*).

2. Mathematical model

The multiechelon model for the biodiesel SC includes 12 products (seed, oil and flour from soy, sunflower and jatropha, pure and blending biodiesel and glycerol), 8 production technologies (fields, crushing plants, biodiesel plants and blending plants), 3 product transportation ways (trucks, train, and ships) and a time horizon of 7 years.

2.1 Mass Balances

Mass balances are given by Eq. (1) and must be satisfied for each product *i* in each region *g* and time period *t*. The equation states that the inventory *SW* at previous time period plus the production *PR*, mass purchase *IP* and mass quantity transported *Q* from other regions *g'* to region *g* must be equal to the current inventory plus product sales *DP*, mass consumed as raw material and mass transported toward other regions. *PP*(*i,p*) is the set of products *i* produced by production technology *p* and *PRM*(*i,p*) is the set of products *i* used as raw materials in production technology *p*. Index *l* is introduced to take into account different modes of product transportation.

$$\begin{aligned} SW_{ig\ t-1} + \sum_{p \in PP(i,p)} PR_{ipgt} + IP_{igt} + \sum_{l}\sum_{g'} Q_{il\ g'gt} = \\ SW_{igt} + DP_{igt} + \sum_{p \in PRM(i,p)} PR_{ipgt} + \sum_{l}\sum_{g'} Q_{il\ gg't} \qquad (1) \\ \forall\, i,g,t \end{aligned}$$

Consumed and produced products are related by mass balance in each production technology *p*. Equation (2.1) shows mass balances in every field sown with soybean and sunflower crops, where A is the sown surface area (hectares) and η the corresponding yield (ton./hectare) for each region and time period projected from historical and statistical data for Argentina. On the other hand, jatropha is a perennial non-food crop with an increasing yield in the first 5 years, being stabilized in the rest of its life-cycle (40 to 50 years). This issue is modeled with Eq. (2.2), where total seed production for a given time period *t* will be calculated as the summation over surface areas sown in different time period $t' \leq t$ multiplied by the corresponding yield.

$$PR_{ipgt} = \eta_{ipgt}\ A_{igt} \qquad \forall\, i = 1..2,\, p = 1..2,\, g, t \qquad (2.1)$$

$$PR_{ipgt} = \sum_{\substack{t' \\ t' \leq t}} \eta_{ipg(t-t'+1)}\ A_{igt'} \qquad \forall\, i = 3,\, p = 3,\, g, t \qquad (2.2)$$

As it is shown in Figure 1, product conversion in crushing and biodiesel plants is represented by mass balance coefficients for each product associated with a production technology and considering unitary coefficients for main products. Equation (2.3) represents mass balances for each technology *p*, where *i'* is the main product and μ is the corresponding mass balance coefficient (ton. of product *i*/ton. of main product).

$$PR_{ipgt} = \mu_{ip} \sum_{i' \in MP(i',p)} PR_{i'pgt} \quad \forall\, i > 3, p > 3, g, t \quad (2.3)$$

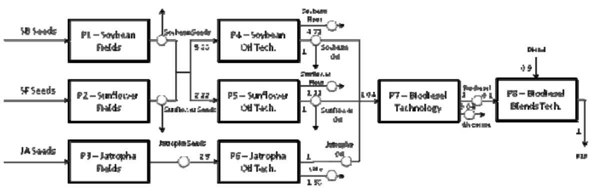

Figure 1. Superstructure of Technologies

2.2 Crop Competition

Considering land usage within supply chain analysis allows taking into account the limited land extension, climate and edafic aptitude for the different raw materials. Eq. (3) states that the total surface area sown with each product *i* is limited by the total available land area to be sown (AA_{gt}) in each region and period.

$$\sum_i A_{igt} \le AA_{gt} \quad \forall\, g, t \qquad (3)$$

The available area to be sown with jatropha in period *t* is given by Eq. (4). This surface should be less or equal than the total available land area in period *t* less soybean and sunflower dedicated area in that period, less the area sown with jatropha in previous time periods *t'*. Due to the fact that jatropha is a new product and its market is being developed, a factor λ_{gt} has been introduced to represent the real crop evolution, e.i., although 1 million of hectares will be available to be sown with jatropha in the first year of the time horizon, the market has not enough response to sow all free area.

$$A_{JA,gt} \le \lambda_{gt} \left(AA_{gt} - A_{SB,gt} - A_{SF,gt} \right) - \sum_{\substack{t' \\ t'<t}} A_{JA,gt'} \quad \forall\, g, t \qquad (4)$$

2.3 Plants Capacity

Plants capacity *CP* is limited by upper and lower bounds as indicated by Eqs. (5) and (6), where the minimal production level in each region is obtained affecting the installed capacity with the factor $\alpha(p) \le 1$. As it can be noted, the summation is over *i* products belonging to set *MP,* as plant capacity is calculated in terms of the main product of each production technology. The capacity of the production technology *p* at region g in any time *t* is calculated from Eq. (7) by addition of existing capacity at the end of the previous period and the expansion in capacity carried out in *t (CEP)*. Upper and lower bounds of these expansions are given by Eq. (8) and (9) where an integer variable *NP* is included, providing information about the number of plants to be installed in every region *g* and period *t*. In these definitions, we have added 2.415 integer variables to the model (considering a time horizon of 7 years).

$$\sum_{i \in MP(i',p)} PR_{ipgt} \le CP_{pgt} \quad \forall\, p, g, t \qquad (5)$$

$$\sum_{i \in MP(i',p)} PR_{ipgt} \ge \alpha_p \, CP_{pgt} \quad \forall\, p, g, t \qquad (6)$$

$$CP_{pgt} = CP_{pg(t-1)} + CEP_{pgt} \quad \forall\, p, g, t \qquad (7)$$

$$CEP_{pgt} \le UBQP_p \, NP_{pgt} \quad \forall\, p, g, t \qquad (8)$$

$$CEP_{pgt} \ge LBQP_p \, NP_{pgt} \quad \forall\, p, g, t \qquad (9)$$

2.4 Storage Capacity

2.4.1 Warehouses Capacity

The stored quantity of product *i* in each warehouse is limited by the capacity of storage (*CS*) in the region *g* and period *t* for this product, and is shown by Eq. 10. As in the previous item, we have included the possibility of built new warehouses (*NS*) for each product, in each region and period. Then, Eq. (11) to Eq. (13) matches with the corresponding plants capacities equations (7 to 9).

$$\sum_i SW_{igt} \le CS_{igt} \quad \forall\, i, g, t \qquad (10)$$

$$CS_{igt} = CS_{ig(t-1)} + CES_{igt} \quad \forall\, i, g, t \qquad (11)$$

$$CES_{igt} \le UBQS_i \, NS_{igt} \quad \forall\, i, g, t \qquad (12)$$

$$CES_{igt} \le LBQS_i \, NS_{igt} \quad \forall\, i, g, t \qquad (13)$$

Following Shapiro (2001), Eq. (14) considers the storage capacity of region *g* in period *t* as twice the average storage level (*ASL*) calculated dividing the amount of sold product (*DP,* warehouse output flow) into the turnover ratio (*TOR*) of product *i*, for the same region and period (see Eq. 15).

$$2\, ASL_{igt} \le CS_{igt} \quad \forall\, i, g, t \qquad (14)$$

$$ASL_{igt} = \frac{DP_{igt}}{TOR_i} \quad \forall\, i, g, t \qquad (15)$$

2.4.2 Ports storage capacity

Storage capacity in ports has an important role due to the large amounts of product exports. The output flow is calculated as exports plus domestic transportation to other internal regions by ships and barges. In this model, storage capacity in ports, unlike warehouse storage capacity, has been considered as a parameter.

$$2\, ASLP_{igt} \le CSP_{igt} \quad \forall\, i, g :: PORTS, t \qquad (16)$$

$$DE_{igt} + \sum_{\substack{g' \\ g' \in PORTS \\ g' \neq g}} Q_{i\,'SHIP'g\,g'\,t} = ASLP_{igt}\ TOR\ \ P_i \qquad (17)$$

$$\forall\, i, g \in PORTS, t$$

2.5 Sales

Eq. (18) shows that total sales are composed of domestic sales and exports. Lower and upper bounds have been imposed, considering the local demand (*DDM*) affected by the factor *Dsat* that stands for the minimum desired satisfaction level and taking into account a time projection for product requirement in international markets (GE=3%)

$$DP_{igt} = DD_{igt} + DE_{igt} \quad \forall\, i,g,t \qquad (18)$$

$$DD_{igt} \le DDM_{igt} \quad \forall\, i,g,t \qquad (19)$$

$$DD_{igt} \ge Dsat_{igt}\ DDM_{igt} \quad \forall\, i,g,t \qquad (20)$$

$$DE_{igt} \le EMAX_i\ (1+GE)^{t\text{-}1} \quad \forall\, i,g,t \qquad (21)$$

$$DE_{igt} \ge EMIN_i\ (1+GE)^{t\text{-}1} \quad \forall\, i,g,t \qquad (22)$$

2.6 Transport Links

The quantity transported between different regions is limited by upper and lower bounds, as indicate by Eq. (23) and (24). In these equations, binary variables have been associated to each transport technology between different regions in each time period for each product able to be transported. In order to reduce total quantity of binary variables, we have modeled shipping between echelons of the supply chain as annual contracts. It means that if the contract is signed ($X_{igg't} = 1$), the transport of this product *i* between these two regions *g* and *g´* could be occur in all periods of the year referred, with minimal and maximal quantities determined by the Eq. (23) and Eq. (24). And if the contract does not exist ($X_{igg't} = 0$), the transport cannot occur. This feature allows to reduce the quantity of binary variables from 6.072 [Binary Vars / periods] to 6.072 [Binary Vars / year]

$$\sum_l \sum_t Q_{il\,gg'\,t} \le\ QUP_{ilt}\ X_{igg'\,t} \qquad \forall\, i,g,g' \neq g,t \quad (23)$$

$$\sum_l \sum_t Q_{il\,gg'\,t} \ge\ QLO_{ilt}\ X_{igg'\,t} \qquad \forall\, i,g,g' \neq g,t \quad (24)$$

Equation (25) means that transports of product *i* in period *t* from region *g* to *g´* cannot occur both with the transport of the same product from region *g´* to *g* in the same period.

$$X_{igg'\,t} + X_{ig'gt} \le 1 \quad \forall\, i,g,g' \neq g,t \qquad (25)$$

2.7 Objective Function and Economic Constraints

The optimization of MILP mathematical model has been carried out maximizing the biodiesel supply chain Net Present Value (*NPV*) given in Eq. (26), where all cash flows *CF* are discounted up to the present with a discount rate *IR*, and *MV* is the market value of the investments at the end of time horizon. All economic variables have been calculated with the convention of End of Year with the exception of Fixed Capital Investment. The amount of money invested in the supply chain at the beginning of year *t*, will begin to produce benefits from year *t+1* onwards.

$$NPV = \left(\sum_t \frac{CF_t}{(1+IR)^t} \right) + \frac{MV}{(1+IR)^{t_{END}}} \qquad (26)$$

Results and Discussion

In this work, we consider three types of raw material (soybean, sunflower and jatropha seeds), the corresponding oil and flour, pure and blending biodiesel and glycerol), eight production technologies (fields, crushing plants, biodiesel plants and blending plants), three product transportation technologies (trucks, train, and ships) and a time horizon of 7 years (2012-2018), divided into 84 time periods. The resulting MILP problem has 468,961 continuous variables and 44,436 discrete ones, from which 42,504 are binary variables. Table 1 shows computational detail as, as well as objective function optimal value.

Table 1. Computational Details

# Equations	177,080
# Continuous Variables	468,961
# Discrete Variables	44,436
NPV [MM USD]	77,190
Solver	CPLEX 11.2
Gap [%]	0.0099 %
Resolution Time	4’ 46.370’’

Processor → Intel Core 2 Duo P8600 2.40 GHz – 3 GB RAM

Optimal distribution of total land for crops considered in this work is shown in Fig. 2 along the entire time horizon. As it can be seen in this figure, an increment of sown land with soybean of 40% in the seventh year and 100% for sunflower is required to satisfy increasing internal and external demand of biodiesel and byproducts (mainly sunflower oil), while an strong increase of jatropha plantations (on the order of 350% for the fifth year) indicates the trend to replace biodiesel production with traditional crops by alternative ones. This trend is remarkable in regions with larger marginal zones and extreme climatic conditions, like Chaco, a northern region in Argentina.

Figure 3 shows a detail of sown areas in the Chaco region. There is an important increase of areas dedicated to jatropha, while areas dedicated to soybean crops remains without changes, indicating that alternative crops are preferred to cover future biodiesel demand. Additionally, more land is necessary to sow sunflower, mainly as a result of the major demand of sunflower oil.

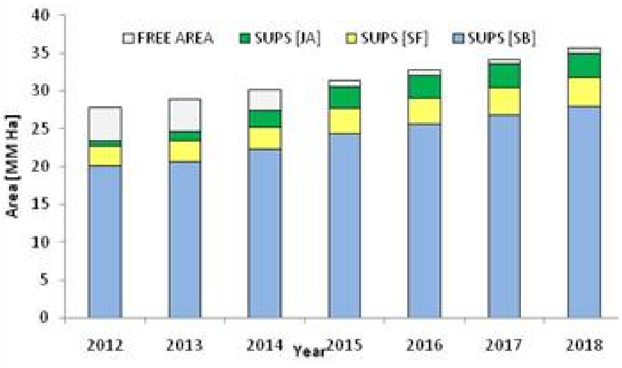

Figure 2. Optimal surface area distribution for soybean (SB), sunflower (SF) and jatropha (JA) crops from years 2012 to 2018

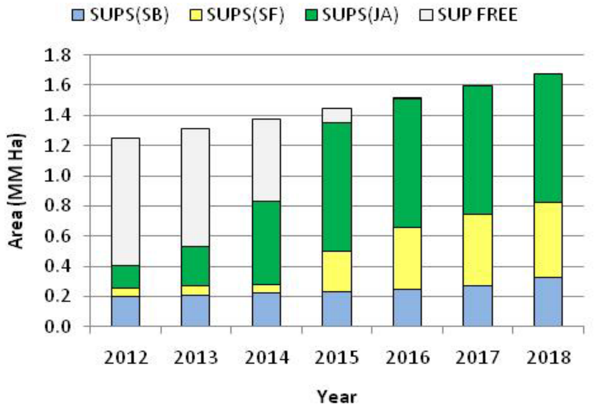

Figure 3. Optimal surface area distribution for soybean (SB), sunflower (SF) and jatropha (JA) crops for a northern region in Argentina (Chaco).

Plant and storage capacities must be expanded to process the increasing flow of raw materials. Numerical results show that fifty four new production plants (oil plus biodiesel) must be incorporated to the Argentinean biodiesel supply chain along the seven years time horizon, to increase biodiesel capacity in 1,800,000 ton/y. Within the new plants, forty two are oil plants and twelve are biodiesel ones, as it can be seen in Figs. 4 and 5, respectively. Regarding warehouses, a total of 154 must be installed; from which forty three are jatropha flour warehouses (currently there are neither plants nor warehouses based on jatropha raw material), one pure biodiesel warehouse and eighteen are biodiesel blended warehouses. It can be seen that new biodiesel plants and warehouses are mainly built in regions where there are currently no plants and they correspond to marginal areas where jatropha is being sown. Current capacity for biodiesel production per region is 700,000; 400,000; 375,000; 60,000; 90,000; 3,100,000 and 150,000 ton/y for Buenos Aires, Córdoba , Entre Ríos, Neuquén, San Luis, Santa Fe and Santiago del Estero

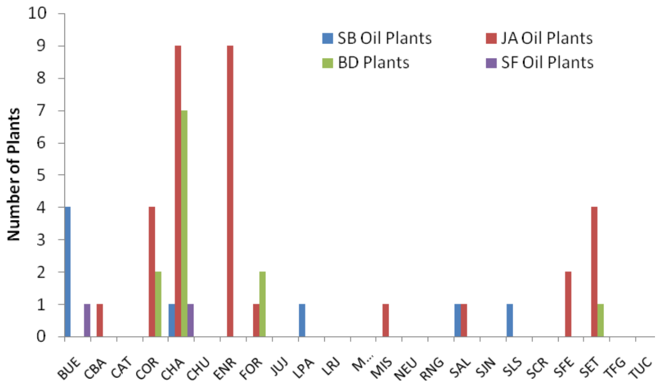

Figure 4. Number of new plants to be built per region (23 regions) throughout the entire time horizon (2012-2018)

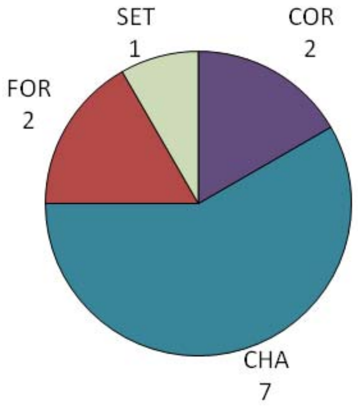

Figure 5. Number of new biodiesel plants per region to be built in the period 2012-2014

regions. Figure 6 shows a detail of the geographical distribution of new jatropha oil plants. It can be seen that the main regions are those with marginal areas where jatropha is sown along the time horizon.

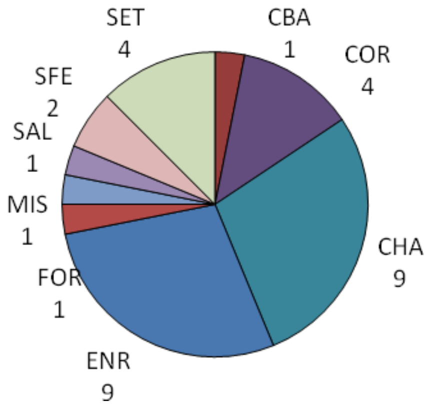

Figure 6. Number of jatropha oil plants to be built per region throughout the entire time horizon (2012-2018)

Results also determine directions and transport mode for intermediate and final products among the twenty three geographical regions.

Conclusions

Optimization of the Argentinean biodiesel supply chain has been performed in this work, taking into account sowing areas for different raw materials up to intermediate and final product distribution in internal and external markets. Numerical results show that the sustainable development of biodiesel supply chain in Argentina requires an increasing use of land to produce oil and flour to satisfy future domestic and external demand, as well as a gradual replacement of traditional crops by alternative ones (jatropha) to produce biodiesel. The mathematical model has been implemented in GAMS providing a powerful decision-making tool that can be applied to other regions or countries by adjusting specific data.

Acknowledgements

The authors gratefully acknowledge financial support from the National Research Council (CONICET), Universidad Nacional del Sur and ANPCYT, and Universidad Nacional del Comahue, Argentina.

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