Supply chain of sugarcane and its lignocellulosic biomass biorefineries in Argentina - An optimal design approach

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Abstract. The sugarcane, a vast agricultural resource, is a key source for sustainable processes yielding biofuels and bioproducts. Tucumán province in Argentina is the main national sugarcane producer with the potential to fully take profit of this biomass in biorefineries. This study focuses on the use of mathematical programming to make strategic decisions in the Argentinean sugarcane industry. The main goal is to transform the traditional production scheme in a complex of biorefineries, which produce multiple products while making an integral use of biomass. The design task is formulated as a mixed-integer linear model (MILP) that seeks to minimize the total cost of the network. The capabilities of the proposed optimization framework are illustrated through a case study based on three real-scaled scenarios. The solutions provide valuable insight into the design problem and suggest different SC topologies.

Keywords: Math programming, Optimization, Bioproducts.

1 Introduction

Sugarcane is the largest agricultural crop by volume globally [1]. Then, the sugarcane industry is ready to be a key participant in the growth of biofuel and bioproduct industries worldwide [2].

To tackle the global challenges of developing sustainable industries and processes on the basis of sugarcane, significant improvements should be made in the area of integrated logistics for sugarcane and its derivatives, reduction of process water and energy use, by-products valorization, second-generation (2G) ethanol production, among others [3].

Tucumán (province) is the main producer of sugarcane in Argentina [4]. Its production of sugar and first-generation (1G) bioethanol meets national quota throughout the country [5]. Cane sugar supplies the domestic market as food and the food and beverage industry demands. Bioethanol is used for fuel blending (regulated by national laws) in an ethanol/fuel ratio of 12%.

Some factories use bagasse (lignocellulosic residue after sugarcane milling) to generate steam and electrical energy, covering the energy needs of the process. However, both bagasse and agricultural harvest residues (AHR) are lignocellulosic materials that contain polymers in their structure from which sugars [6] and other valuable products [7] can be obtained.

The sugarcane supply chain (SC) management is a complex task in which many decisions of design, production planning and products distribution needs to be made. This study focuses on the use of mathematical programming to derive optimal strategic decisions about the industry of the sugarcane, including its lignocellulosic biomass, in Argentina. The main goal is to transform the sugarcane SC into an integrated network of biorefineries capable of producing multiple products through the integral use of the available biomass.

2 Problem statement

The goal of this study is to propose a mathematical model to determine the configuration of a three-echelon (production-storage-market) sugarcane-based biorefinery SC and associated planning decisions that minimize the total costs to satisfy a given products demand. Decisions to be made include the type (technologies), number, location, capacity and production level of the biorefinery plants, warehouses to be set up in different regions, transportation links and transportation modes that need to be established in the network, and product rates delivered to the markets.

3 Mathematical model

In this section, we present a mixed-integer linear programming (MILP) formulation that models the sugarcane SC described above. Only the most relevant mathematical expressions are described. The following SC activities in the Argentinean sugarcane industry, both current and potential, are included in the approach: biomass production, industrialization, products storage, purchasing and transportation. In addition, the model is characterized by being multi-period, multi-raw material and multi-product. Indices and sets used in the model are shown in Notation section.

The objective function is represented by the total costs associated to the SC and consists of the sum of the costs related to biomass production (TMC), installation of biorefineries and their production levels (TBC), installation of warehouses and their average inventory levels (TSC) and the setting of transportation links for raw materials and products (TTC) along the SC.

TMC are calculated by multiplying the unit production costs of each type of raw material (θ_i^V) by the annual amount of raw material required in region g ($H_{i,g,t}$) and in other regions (the second term in parentheses), Eq. 1. Two raw materials are considered: sugarcane, whose cost includes its cultivation and harvest; and agricultural harvest residues (AHR) including its windrowing and baling. The investment cost of the machinery is not considered.

$$TMC_t = \sum_{g \in GH} \sum_{i \in IR} \theta_i^V \left(H_{i,g,t} + \sum_{IL(i,l),g' \in GB(g)} Q_{i,l,g,g',t} \right) \ \forall t \quad (1)$$

Requirements of raw materials are limited by the capacity of the existing sugarcane plantation in regions GH(g) ($CapCrop_{i,g,t}$), Eq. 2. $\eta_{i,g,t}$ represents the percentage variability of the average production capacity due to climatic conditions.

$$H_{i,g,t} + \sum_{IL(i,l),g' \in GB(g)} Q_{i,l,g,g',t} \leq \frac{\eta_{i,g,t}}{100} CapCrop_{i,g,t} \quad \forall i \in IR, g \in GH, t \tag{2}$$

TBC are made up of the fixed costs associated with the installation of each technology according to production level ($\theta^{F}_{k,c}$) and its unit production costs (θ^{V}_{k}), Eq. 3. The binary variable $z_{k,c,g,t}$ is equal to 1 if the technology k with a capacity c is installed in a region g, and 0 otherwise; while $X_{k,g,t}$ is its required production level, expressed in metric tons per year.

$$TBC_t = \sum_{g \in GB} \sum_k \sum_c \theta^{F}_{k,c}\, z_{k,c,g,t} + \sum_{g \in GB} \sum_k \theta^{V}_{k}\, X_{k,g,t} \quad \forall t \tag{3}$$

The production level of a given technology is limited, in Eq. 4, by the selected installed capacity ($Kcapmax_{k,c}$). Eq. 5 and 6 represent existence constraints associated to the installation of biorefineries and technologies in a region in GB(g). The binary variable $y_{c,g,t}$ is equal to 1 if a biorefinery (and its technologies) with an overall capacity c is installed in a region g, and 0 otherwise.

$$X_{k,g,t} \leq \sum_c z_{k,c,g,t} Kcapmax_{k,c} \quad \forall k, t, g \in GB \tag{4}$$

$$z_{k,c,g,t} \leq y_{c,g,t} \quad \forall k, c, t, g \in GB \tag{5}$$

$$\sum_c z_{k,c,g,t} \leq 1 \quad \forall k, t, g \in GB \tag{6}$$

Once a biorefinery is installed in a GB(g) region, the general mass balance must be met for each material (Eq. 7). It establishes that the quantity that enters the biorefinery through the different types of transportation and the available amount in the region, added to the quantity produced onsite (in k technologies K^{+}), must be equal to the consumption of this material (in other technologies K^{-}) plus what comes out of it and is transported to other regions. For all materials, it is allowed to have an unprocessed or effluent quantity that results in the continuous variable $EF_{i,g,t}$. This amount, such as biogas or electric energy, can then be used by other technologies.

$$\sum_{IL(i,l),g' \in GH(g), i \in IR} Q_{i,l,g',g,t} + H_{i,g,t} + \sum_{k \in K+} \rho_{i,k} X_{k,g,t} = \sum_{k \in K-} \rho_{i,k} XL_{i,k,g,t} + \sum_{IL(i,l),g' \in GS(g), i \in IM} Q_{i,l,g,g',t} + EF_{(i,g,t)} \quad \forall i, t, g \in GB \tag{7}$$

The variable $H_{i,g,t}$ is nonzero if there is an installed biorefinery in the same region from which the biomass comes (Eq. 8), where BigM is a large enough scalar.

$$H_{i,g,t} \leq \left(\sum_c y_{c,g,t}\right) BigM \quad \forall i \in IR, t, g \in GB \tag{8}$$

As is common in a biorefinery context, there are cases where multiple raw materials or intermediate products could enter the same technology to meet the desired output. Then, the production level for K^{-} technologies can be satisfied from streams of different materials (Eq. 9).

$$X_{k,g,t} = \sum_{i \in K^{-}_{(k,i)}} XL_{i,k,g,t} \ \forall k, t, g \in GB) \tag{9}$$

The model allows for the installation of technologies to produce biogas from the treatment of vinasses or technologies to produce electrical energy from lignocellulosic materials in order to reduce the external energy consumption of the biorefinery. This strategy of energy flows recirculation stands out as a tool for circular economy implementation in industrial systems. Eq. 10 and 11 show the constraints in energy flow balances that must be met. It is exemplified for the case of recirculation of biogas. The first member of Eq. 10 represents consumption of natural gas in the biorefinery, the second member, two alternatives to supply those needs: biogas produced *in-situ* (BGP) or external natural gas (NGP). The former is constrained by the process (Eq. 11).

$$\sum_k \xi_k X_{k,g,t} = NGP_{g,t} + BGP_{g,t} \ \forall t, g \in GB \tag{10}$$

$$BGP_{g,t} \leq EF_{biogas,g,t} \ \forall t, g \in GB \tag{11}$$

TSC are calculated as the sum of the cost necessary to install a warehouse of a determinated capacity and the variable costs associated with the annual average inventory level (AIL) of each product (Eq. 12). The binary variable $w_{c,g,t}$ is equal to 1 if a warehouse with an overall capacity c is installed in region g, and 0 otherwise.

$$TSC_t = \sum_{g \in GS} \sum_c \theta^F_c \times w_{c,g,t} + \sum_{g \in GS} \sum_{i \in IM} \theta^V_i \times AIL_{i,g,t} \ \forall t \tag{12}$$

The installed warehouse capacity must be at least twice the AIL of products in the warehouse (Eq. 13), which can be calculated based on empirical values by an expression of the exponential type dependent on the product throughput [8]. In order to maintain the model linearity, a piecewise linear approximation is performed through integer mixed programming.

$$\sum_{i \in IM(i)} 2AIL_{i,g,t} \leq \sum_c w_{c,g,t} CAP_{c,s} \quad \forall i \in IM(i), g \in GS(g), t \tag{13}$$

The final products can be stored in the GS(g) regions where a material balance must be met for each final product (Eq. 14). The summations represent the product flows that are transported from the biorefineries from GB(g) to regions warehouses from GS(g) (in the first member of the equation) and the product flows that are transported from the warehouses to the demand centers GD(g) (in the second member of the equation). $S_{i,g,t}$ is the inventory of a product at the end of year t while $S_{i,g,t-1}$ is the one in the previous year. $M_{i,g,t}$ is the amount required in GS(g) to meet the demand in this region and only exist if there is an installed warehouse in the same region (similar constraint to Ec. 8).

$$\sum_{l,g' \in GB(g)} Q_{i,l,g',g,t} + S_{i,g,t-1} = S_{i,g,t} + M_{i,g,t} + \sum_{l,g'' \in GD(g)} Q_{i,l,g,g'',t} \quad \forall i \in IM(i), g \in GS(g), t \tag{14}$$

The destination of the final products is the demand center for each product, where the quantity of different final products transported from storage centers must meet or exceed the demand requirements ($D_{i,g,t}$), Eq. 15 and 16.

$$\sum_{l,g' \in GS(g)} Q_{i,l,g',g,t} + M_{i,g,t} = J_{i,g,t} \quad \forall i \in IM(i), g \in GD(g), t \tag{15}$$

$$J_{i,g,t} \geq D_{i,g,t} \quad \forall i \in IM(i), g \in GD(g), t \tag{16}$$

Regarding transportation, three transportation modes (l) are considered: for raw materials, for solid products and for liquid products. TTC are composed of the costs of transportation between the different nodes of the SC: from biomass production in regions to biorefineries (TTCa, Eq. 17), from biorefineries to storage centers (TTCb) and from storage centers to demand centers (TTCc). The costs of each transportation step depend on the number of trips per year (NL) and are made up of general costs (GE), fuel costs (FP), salary costs (DW) and maintenance costs (ME). $d_{g,g'}$ and $t_{g,g'}$ represent the distance and travel time, respectively, between regions g and g '.

$$TTCa_t = \sum_{l,g \in GH, g' \in GB} \sum_{i \in IR} NL_{i,l,g,g',t} [2GE_{i,l} + FP(FC_{1l} d_{g,g'} + FC_{2l} d_{g',g}) + DW_l (t_{g,g'} + t_{g',g} + LUT_l) + ME_l (d_{g,g'} + d_{g',g})] \; \forall t \tag{17}$$

To calculate number of trips there is a constraint related to the minimum and maximum capacities of each type of transport ($Lcapmin_l$ y $Lcapmax_l$) and the quantities that need to be transported between SC nodes, $Q_{i,l,g,g',t}$, (Eq. 18 for NL in TTCa).

$$Lcapmin_l NL_{i,l,g,g',t} < Q_{i,l,g,g',t} < Lcapmax_l NL_{i,l,g,g',t} \quad \forall i \in IR(i), g \in GH(g), g' \in GB(g'), t, l \tag{18}$$

4 Case Study

The main objective of this case study is to illustrate the capabilities of the proposed model. Based on the sugarcane industry of Tucumán (Argentina), the following scenarios are studied:

A. Base case: Current demand situation (white sugar and ethanol production).

B. Biorefinery case 1: it is considered a change of national regulations that increase the ethanol/fuel blending percentage to 25%, which implies a demand increase for sugarcane-based bioethanol. The increase in ethanol demand should be covered by 2G ethanol, while demands for white sugar and 1G ethanol remain as in the base case.

C. Biorefinery case 2: it is decided to implement technologies to diversify the sugarcane industry through the production of bioproducts. Lactic acid is selected and its demand is added while demands for ethanol and white sugar are kept as in case A.

As can be seen from the previous section, the model is capable of considering multiple periods. However, in the case study, the time horizon has been reduced to a single period to focus attention on those issues related to the structural aspects of the solutions.

The geographic scope of the problem has been defined according to the administrative divisions of Tucumán (departments) and Argentina (provinces) (Fig. 1). Biomass producing regions, GH(g), and regions of potential location of biorefineries, GB(g), are G01 to G17 (within Tucumán province). Also, potential location of warehouses, GS(g), and regions with product demands, GD(g), are G18 to G40 (outside Tucumán province). Therefore, 23 provinces of Argentina and 17 departments of Tucumán are considered, resulting in a total of 40 regions for the model.

Fig. 1. Geographic regions considered.

Distance and travel time between regions are two parameters that depend on geography. These are obtained through the R-package *GmapsDistance* that computes the values from Google's servers. *GmapsDistance* is an open-source tool that connects the R programming language with Google Maps. Other parameters referring to transportation are taken from previous studies [9][10].

GH(g) regions are assigned their biomass availability in metric tons of sugarcane harvested for year (CapCrop). These parameters are estimated considering geographical distribution of crops [11] and harvest yields according to technology levels in agricultural practices [12]. While to GB(g), demands of ethanol and sugar per region are assigned and taken from national reports [5]. It is considered that 151 kg of AHR are produced per metric ton of harvested sugarcane. In addition, for reasons of soil protection and nutrition, 50% of these residues are considered to be left in the fields. Unit production costs associated to raw materials production are taken from local studies and estimations [13][14] and [15][16].

Biorefineries production technologies. The model is given the possibility of installing biorefineries of different overall capacities (small = 267 kt / year, medium = 838 kt / year and 2273 kt / year) considering current capacities of the facilities in Argentina [5]. Sugarcane could enter the milling process (K00) to obtain juice and a lignocellulosic residue called bagasse (Fig. 2). Sugarcane juice could be processed then by different technologies (K06, K07 and K10). K06 and K07 technologies use sugarcane juice to produce white sugar and raw sugar, K06 generates molasses as a byproduct and K07 generates secondary honey (byproducts differ principally in their sucrose content). Bioethanol can be produced by fermentation of molasses (K08), honey (K09) or sugarcane juice (K10). The ethanol production residues are vinasses, the properties of which depend on the raw material used in the process and could be processed to obtain biogas through anaerobic fermentation (K15).

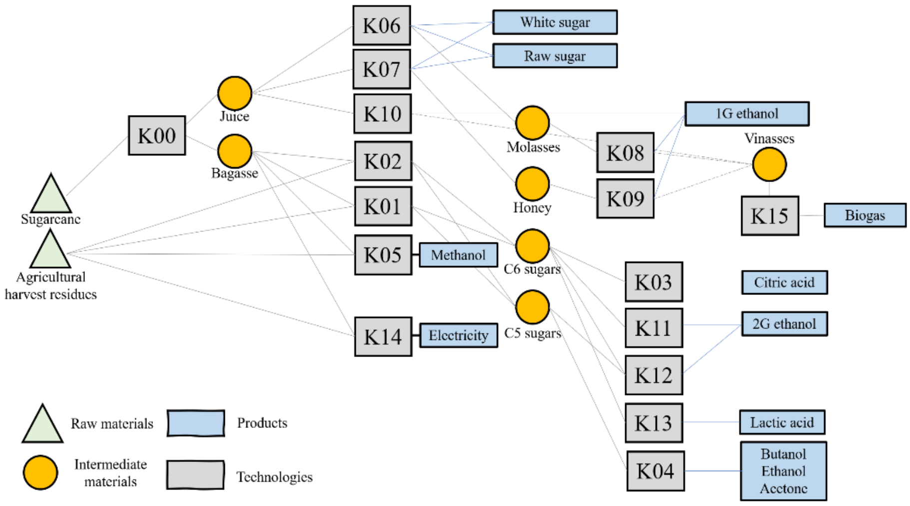

Fig. 2. Materials and technologies considered.

Bagasse and AHR are lignocellulosic fractions of the sugarcane plant from which hydrolyzed sugars can be obtained. A characterization work has been done on this lignocellulosic material in Tucumán [6], where its attractiveness for the production of sugars is highlighted due to its high carbohydrate content. Likewise, there are, as in-progress research, several technologies to obtain C5 and C6 chemicals by processing these sugars with the ultimate aim of obtaining biofuels and high-value products. Technologies to produce C5 and C6 sugars from the available lignocellulosic materials (K01 and K02) and their subsequent processing to obtain methanol (K05), electricity (K14), citric acid (K03), 2G ethanol from C6 sugars (K11), 2G ethanol from both C5 and C6 sugars (K12), lactic acid (K13) and butanol (K04) are included in the model. Yields and economic parameters are obtained from bibliography [9][17-24]. Electricity and natural gas consumptions are also retrieved from these sources. The model is given the possibility of installing technologies in biorefineries of three overall capacities (small, medium and large), with values depending on the technology. The investment costs of each technology ($\theta^{F}_{k,c}$) are extracted from the literature and scaled to be incorporated as parameters in the model.

Table 1. Product demand (ton/year)

Province name	Region index	White sugar	1G ethanol	2G ethanol		Lactic acid	
		A, B and C	A, B and C	A and C	B	A and B	C
Buenos Aires	G18	96281	34718	-	37611	-	15000
Córdoba	G19	105721	38122	-	41299	-	20000
Corrientes	G20	31968	11527	-	12488	-	-
La Plata	G21	476625	171867	-	186190	-	15000
La Rioja	G22	12208	4402	-	4769	-	-
Mendoza	G23	54748	19742	-	21387	-	-
Neuquén	G24	17243	6218	-	6736	-	-
Entre Ríos	G25	39645	14296	-	15487	-	-
Misiones	G26	34108	12299	-	13324	-	-
Chubut	G27	14474	5219	-	5654	-	-
Chaco	G28	33227	11981	-	12980	-	-
Santa Cruz	G29	7173	2587	-	2802	-	-
Salta	G30	38639	13933	-	15094	-	-
San Juan	G31	22025	7942	-	8604	-	-
San Luis	G32	13844	4992	-	5408	-	-
Jujuy	G33	21521	7760	-	8407	-	-
Santa Fe	G34	101945	36761	-	39824	-	-
La Pampa (General Pico)	G35	10572	3812	-	4130	-	-
Santiago	G36	27311	9848	-	10669	-	-
Catamarca	G37	10824	3903	-	4228	-	-
Río Negro (General Roca)	G38	18879	6808	-	7375	-	-
Formosa	G39	16990	6127	-	6637	-	-
Tierra del Fuego	G40	4027	1452	-	1573	-	-

Storage facilities. The model can install warehouses of different capacities for the storage of the various products generated in the biorefineries and, from there, to meet the demands in each region of the country. As said before, AIL is calculated using a linear approximation of a function of the product throughput (aV^b) typical of SC strategic planning [8], taking *a* and *b* from [25]. Economic parameters are adapted from [9].

Demand distribution. Table 1 shows the demand parameter for each scenario under study. The annual demand of products for Tucumán are taken from national reports

(MH 2018). For scenario C, it is considered that the use of lactic acid could be as an industrial input and therefore the main demand centers would be G18, G19 and G21, which concentrate the country's industrial activity.

The model is implemented in GAMS® and solved with the MILP solver CPLEX 11.0 on a DELL DESKTOP-OMKAB82 PC with an Intel(R) Core (TM) i5-9500, 3.00 GHz and 8 Gb of RAM. The resulting optimization model contains 22582 equations, 31274 continuous variables, and 10208 discrete variables. The CPU times spent to find the optimal solutions are 4325 s, 12311 s and 859 s for Case A, B and C, respectively, to a less than 1% optimality gap.

5 Results

Fig. 3 and 4 show the main results obtained with respect to the geographic structure of the SC (biorefineries and warehouses installed) and technologies selected for the three scenarios studied.

In cases A and B, it is decided to install nine biorefineries: two small, one medium and six large. These cases only differ in the location of two biorefineries (one small and one large). The selection of technologies and production levels are virtually the same to meet the demands of 1G ethanol and sugar. In case B, three large capacity technologies are added to the G13 region for the processing of lignocellulosic biomass (K01) and production of 2G ethanol (K11 and K12). Bagasse produced by K00 technology and RAC from the same region and from nine other regions are used as lignocellulosic feedstock.

In case C, results vary more considerably with respect to the installation of biorefineries. Here seven large biorefineries are installed in the regions with the greatest amount of sugarcane, while all the technologies installed are those with the highest possible capacity. Additionally, due to the fact that the new demand for lactic acid is relatively small with respect to that of conventional products, and also only three regions demand this product, the storage distribution is identical to case A.

In all the alternatives studied, it is decided to install technologies for the treatment of vinasses with biogas production (K15) to reduce the consumption of external natural gas. Likewise, in the three case studies there are by-products (e.g., raw sugar) and effluents or surplus material (e.g., bagasse, molasses, vinasses, etc.). The latter could be used in other technologies with the aim of maximizing the use of biomass, converting the industrial facilities into true biorefineries with a wide portfolio of products.

The total costs of case A, B and C are $1046 \cdot 10^6$ US$, $1323 \cdot 10^6$ US$ and $1171 \cdot 10^6$ US$, respectively.

Beyond the case studies presented, this model has the possibility of being used with demands that vary over time. Furthermore, it is applied to minimize costs, so as not to obtain results hidden by the uncertainty of the prices of bioproducts that are not yet competing in the market against conventional products. But, if market prices were available, the objective function could reflect the benefits of the solution and the most promising products from this economic point of view.

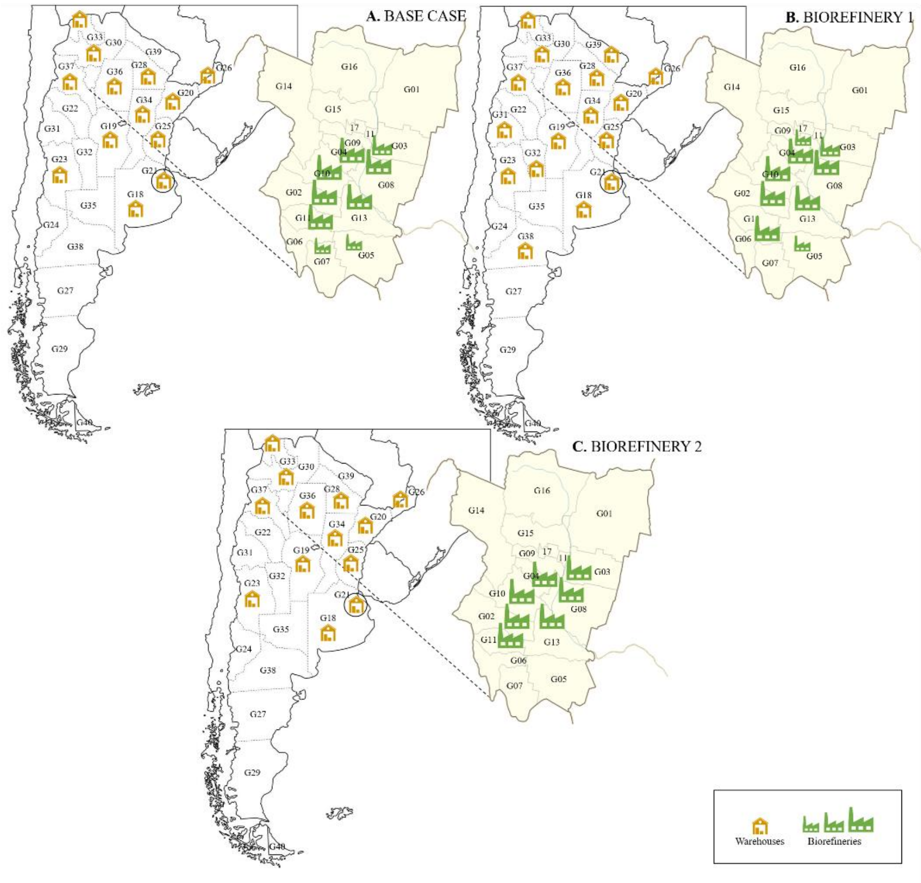

Fig. 3. Optimal location of biorefineries and warehouses for cases A, B and C.

6 Conclusions

This work addresses the optimal design and planning of SCs of the sugarcane-based biorefineries with technical and economic concerns. The design task is formulated as a MILP that seeks to minimize the total cost of the network. The capabilities of the proposed modeling framework are illustrated through a case study based on three real-scaled scenarios. The solutions provide valuable insight into the design problem and suggest different SC topologies according to the value of the model parameters, e.g., unit costs for production, storage and transportation, demand pattern, biomass availability, etc. This tool is devised to assist authorities in the analysis of strategic policies in the field of agro-industries and energy. Future work will focus on adding new features to the model.

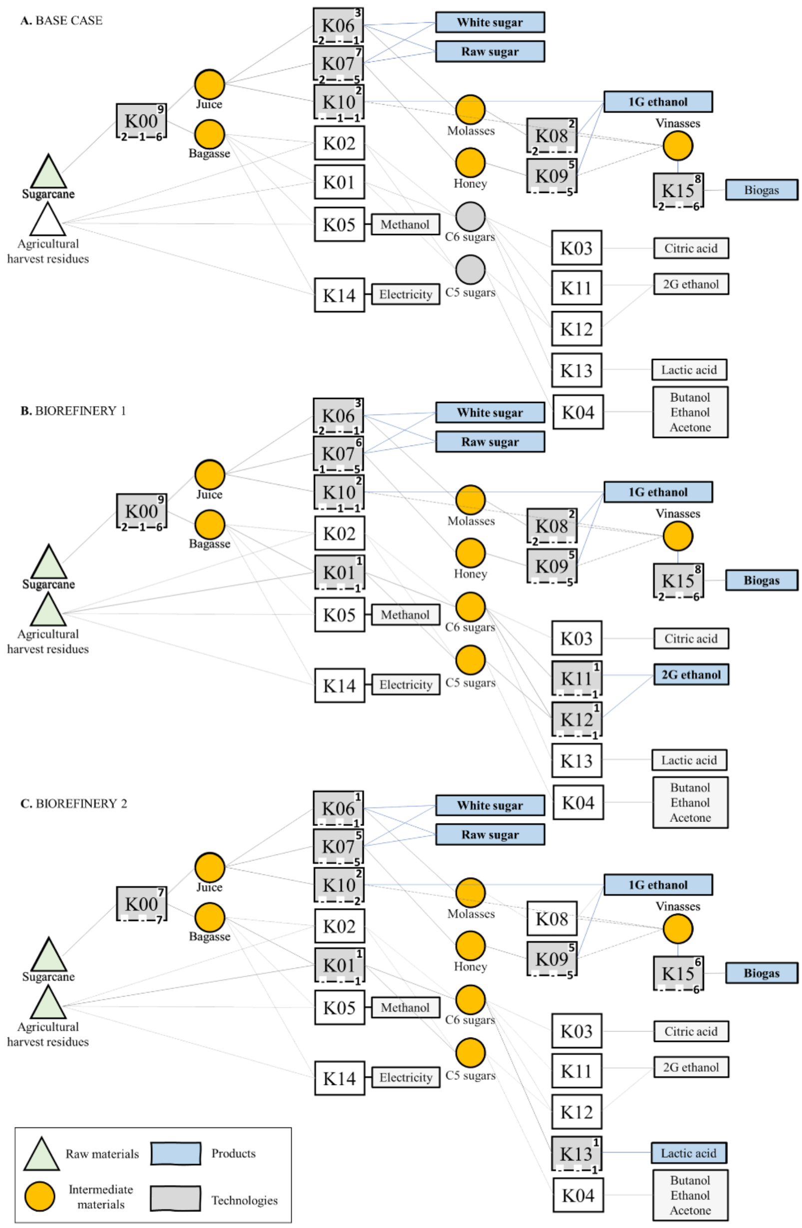

Fig. 4. Pathways and technologies selection in biorefineries installed in cases A, B and C. The numbers within each technology-box indicate: total number of such technology installed (top right), number of small, medium and large capacities installed (bottom, from left to right).

Notation

Indices

i = materials
g = regions
t = time periods
l = transportation modes
k = technologies
c = capacity

Sets

IR(i) = subset of materials that are raw materials
II(i) = subset of materials that are intermediate materials (produced and consumed in the biorefinery)
IM(i) = subset of materials that are final products
GH(g) = subset of regions that can produce raw materials
GB(g) = subset of regions that can install biorefineries
GS(g) = subset of regions that can install storage facilities
GD(g) = subset of regions that have products demand requirements
IL(i, l) = set of set of ordered pairs that link materials i to transport modes l
K^-(k, i) = set of ordered pairs that link technologies k that consume materials i
K^+(k, i) = set of ordered pairs that link technologies k that produce materials i

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