Strategic Planning of Integrated Biofuel and Petroleum Fuel Supply Chains

Aba Michael M. and Galo A. C. Roux

Abstract—**Rising energy demand, dwindling petroleum resources and climate change are the foremost drivers of the energy revolution leading to development of alternative fuels to replace fossil derived energy sources. Biofuels as one of the viable solutions is increasingly becoming part of the energy mix of many nations whose market has become established by biofuel policies and mandates. However, investments in biofuel supply chains can be expensive and several supply chain models have been developed to demonstrate its cost-effectiveness with few models considering coordination with existing petroleum infrastructure and tactical management of feedstock and products. This consideration could have significant impact on cost reduction and effective coordination of both supply chains. Hence, this article presents a multi-period multiscale strategic design and planning model for an integrated ethanol and gasoline supply chain which composes a superstructure that combines all the components of the biofuel and petroleum supply chain. The model presented is a Mixed Integer linear Programming (MILP) model used to identify regions where investments are required and the optimal configuration of the network while also taking into consideration inventory management and transportation logistics. The application of a dynamic capacity strategy also provides information on strategic capacity additions, expansions, contractions and closures. A case study of northeast of Brazil where investments in ethanol bio-refineries is required to equalize the market demand is considered. Results of the case study produce an optimal network configuration with minimal investments in bio-refineries and optimal capacity utilization of plants whereas also ensuring cost is minimized and demand is fully met in all time periods.**

Index Terms—**Biofuels, mixed integer linear programming, strategic planning, supply chain.**

I. Introduction and Literature Review

The shift from non-renewable to renewable energy sources lies at the core of bio-economic developments, this is because a bio-based economy promises less utilization of petroleum fuels, reduction in anthropogenic CO_2 emissions, creation of new employment opportunities, and fostering innovation using cleaner and more efficient technologies. This energy revolution has been catalyzed by rising energy demands, dwindling petroleum resources and climate change which has led to progressive research and development of bioenergy and biorefineries [1].

Although the focus of research has been on biorefinery technology and process development over the years, there has been a shift to more holistic supply chain approaches to ensure sustainability of these biorefineries. Biofuel supply chains comprise the entire stages involved in meeting the energy demand from feedstock acquisition/production to biofuel consumption by the consumer [2], [3]. Several studies have been carried out in this respect, however, most Biofuel Supply chain designs in literature focus on upstream and midstream opportunities for planning and management of biorefineries without seeking out opportunities for integration with existing petroleum infrastructure. As predicted by [2] biofuel demand will be more predictable due to the regulations on Green House Gas (GHG) emissions by many countries which also has the potential to evolve opportunities for integration of petroleum and biofuel supply chains. An integrated approach to biorefinery planning with existing petroleum supply chain brings about benefits of cost-effective coordination, lower fuel blend cost and leverage of existing petroleum infrastructures particularly in transportation and distribution sectors which is seldom considered in biorefinery planning.

Some studies which have explored this concept include the study by [4] who developed a multiscale MILP strategic planning model for an integrated ethanol and gasoline supply chain network composed of a superstructure that combines the components of both supply chains while considering different means of transportation and inventory management. Aggregated and detailed Models were formulated to determine investment hotspots for gas stations and sites for retrofits with blending pumps respectively. Duarte *et al* [5] considered a facility location problem involving plant number and material flows as decision variables in a Colombian context. The authors focused on strategic planning of biorefineries assuming a steady flow of petroleum fuel with a strict blend recipe to meet domestic and international biofuel demands. However, this work does not consider the environmental impacts of the supply chain but was further updated to a multiobjective optimization problem in [6] where the facility location problem was carried out under environmental considerations.

Furthermore, Tong *et al* [7] formulated a multiperiod MILP model that addresses the optimal design and strategic planning of the integrated biofuel and petroleum supply chain system in the presence of pricing and quantity uncertainties. Explicit equipment modelling of units and material streams in the retrofitted petroleum process is done to achieve a higher resolution and improve the overall economic performance, however, environmental objectives were not considered as well. Ivanov *et al* [8] also formulated a MILP model for the strategic planning of an IBSC (integrated biofuel supply chain) using total annualized cost and total life cycle GHG (greenhouse gas) emissions as economic and environmental criteria respectively. The authors included crop rotation conditions to assure the supply of biological feedstock and took into account infrastructure compatibility,

Manuscript received April 28, 2020; revised May 20, 2020.
The authors are with the Departamento de Engenharia Quimica da Escola Politecnica, Universidade de Sao Paulo, Sao Paulo 05508-000, Brazil (e-mail: abamichael489@usp.br, galoroux@usp.br).

demand distribution, size and location of biorefineries using the available biomass and carbon tax data. The security of final energy demand is also ensured to be met at all times.

More recently, A build-up on work done by [7] led to the development of a comprehensive supply chain model for biofuel produced from coffee residues in Colombia developed [9] which considers a dynamic capacity strategy and inventory management in the modelling effort, adding more realism to the system with compliance to long-term and short-term goals. However, a petroleum supply chain was not included in this work.

Consequently, as the world drifts towards considering fuel switching options to combat climate such as biofuels, biofuel supply chain models should be adapted to exploit integration opportunities with existing petroleum supply chain networks while adding dynamism to capacity planning which is considered in this modelling effort.

II. Problem Statement

The problem considered in this work is an integrated biofuel and petroleum supply chain where investments in biorefineries is made with respect to co-location with petroleum refineries, distribution centres and existing biofuel network. Decisions involved in this are optimal location of biorefinery and distribution centres, process technology selection, feedstock source and type, capacity utilization, transportation logistics and inventory management. Furthermore, the objective of this optimization problem is to minimize the Total Cost (TC) of the network. We also consider a time horizon of several years and an overall fuel blend demand is specified and projected according to the average demand growth rate. The model is extended to incorporate a dynamic capacity strategy that determines the addition, expansion (contraction) and closure of facilities to add more realism to the strategic plan. The technical and economic inputs for the problem include:

- Technical (yields) and economic (capital and operating costs) parameters as a function of feedstock type and process technologies;
- Different investment levels for biorefineries and distributions centers
- Capacities of existing petroleum refineries, biorefineries,
- Transport mode options and costs
- Blend demand

III. Model Information

The model was formulated as a MILP framework adapted from [4]. The modelling effort represents the entire integrated supply chain including feedstock harvesting sites, ethanol plants, distribution centers, petroleum refineries, transport mechanism and demand zones. Modifications were made to account for biomass losses during harvesting and storage, aggregated petroleum supply chain and product exports to other continents and inclusion of logical constraints to determine the addition, expansion, contraction and closure proposed by [9]. The objective of the model is to minimize the Total Cost (TC) of the supply chain.

A. Harvesting Sites

The available biomass AB_{bit} that can be used for biofuel production from harvesting site i at period t is defined by equation (1) which is limited by the product of the available land LA_{bi} for biomass b production at harvesting site i, the biomass b yield per hectare BY_{bi} at harvesting site I, a sustainability production allocation limit $\beta ioFlim_{b,t}$ for each biomass b in period t taking into consideration harvest losses HL

$$AB_{bit} = LA_{bi}BY_{bi}\beta ioFlim_{b,t}(1-HL) \quad \forall b,i,t \tag{1}$$

Equation (2) constrains the harvest volume bharv_{bit} to the available biomass AB_{bit} at selected biomass harvest sites (i.e y_{bit}^{i} =1) whereas equation (3) sets the condition that for number harvesting sites for biomass harvest for all biomasses b and periods t

$$bharv_{bit} \leq AB_{bit}y_{bit}^{i} \quad \forall b,i,t \tag{2}$$

$$\sum_i y_{bit}^{i} \leq N^{i} \quad \forall b,t \tag{3}$$

The mass balance for biomass harvest $bharv_{bit}$ and flowrate FIJ_{bijmt} of biomass b from harvesting site i to processing plant j using transportation mode m at period t is given by Equation (4).

$$\mathrm{bharv_{bit}} = \sum_{j,m} FIJ_{bijmt} \quad \forall b,i,t \tag{4}$$

B. Biorefinery

The mass balance of biomass received and consumed at the production plant is described by Equations (5) which states that all biomass inflow and storage inventory from the previous period equals the total biomass consumed plus the amount stored in the current period. Equation (6) provides upper and lower bounds for the inventory levels at the plant, Equation (7) defines the ratio of the biomass b consumed $b\omega j_{bjqt}$ at plant j using technology q at period t to the turnover ratio TOR_b^b of the biomass.

$$\sum_{i,m} FIJ_{bijmt} + SBJ_{bjt-1} = \sum_q b\omega j_{bjqt} + SBJ_{bjt} \quad \forall b,j,t \tag{5}$$

$$h^{min}inventBio_{bjt} \leq SBJ_{bjt} \leq h^{max}inventBio_{bjt} \quad \forall b,j,t \tag{6}$$

$$inventBio_{bjt} = \frac{\sum_q b\omega j_{bjqt}}{TOR_b^b} \quad \forall b,j,t \tag{7}$$

Equation (8) denotes the quantity of biofuel produced through the biomass b consumption in the production process using technology q at plant j. the mass balance of biofuel produced is also described by Equations (9) –(11) describes the mass balance of biofuel produced by technology at plant j and stored inventory at each plant j, the ratio of biofuel production to the turnover ratio and the boundary conditions to the inventory at the plant for all time periods.

$$pwj_{jpqt} = \sum_b (u_{b,q}^{p}\, b\omega j_{bjqt}) \quad \forall j,p,q,t \tag{8}$$

$$\sum_q pwj_{jpqt} + SPJ_{pjt-1} = \sum_{k,m} FJk_{jkmpt} + \sum_{l,m} FJL_{jlmpt} + SPJ_{p,j,t} \quad \forall p,j,t \tag{9}$$

$$inventBP_{jpt} = \frac{\sum_{k,m} FJk_{jkmpt} + \sum_{l,m} FJL_{jlmpt}}{TOR_j^j} \quad \forall j,p,t \tag{10}$$

$$h^{min}.inventBP_{jpt} \leq SPJ_{pjt} \leq h^{max}.inventBP_{jpt} \quad \forall j,p,\mathrm{t} \tag{11}$$

Equation (12) sets the production limits for all plant j using production technology q at period t whereas (13) ensures that new plant capacity $npcJ_{jqst}$ and capacity expansion (or contraction) is always added to current production capacity $Bprod_{jqt}$.

$$\theta_{jq}^{j}\left(EBPC_{jq}^{j} + Bprod_{jqt}\right) \leq pwj_{jpqt} \leq EBPC_{jq}^{j} + Bprod_{jqt} \quad \forall j,p,q,t \tag{12}$$

$$Bprod_{jqt} = Bprod_{jqt-1} + \sum_{s}\left(npcJ_{jqst} + PC_{jqst}^{e}\right) \quad \forall j,q,T \tag{13}$$

The new plant capacities $npcJ_{jqst}$ added to existing capacities for all plants j, technology q and plant size s is restricted by the discrete capacity sizes PC_{qs}^{bp} which can be selected from (Equation 14) and in like manner Equation (15) restricts the expansion (contraction) capacity alternatives that can be added to existing plants. Equations (16) places practical limits on the number of plants that can be established in each year and this can be due to the availability of investment capital limitations.

$$npcJ_{jqst} \leq PC_{qs}^{bp} y_{jqst}^{j} \quad \forall j,q,s,t \tag{14}$$

$$pcap_{jqst}^{je} = \sum_{e} PC_{qse}^{be}\, y_{jqset}^{je} \quad \forall j,q,s,t \tag{15}$$

$$\sum_{q,s} y_{jqst}^{j} \leq N^{j} \quad \forall j,t \tag{16}$$

C. Petroleum Supply

Petroleum supply FRK_{rkmft} from existing petroleum refineries r to the blending centers k using transportation mode m at period t is bounded the refinery capacity $ERPC_{r}$ for all time periods and refineries.

$$\sum_{kmf} FRK_{rkmft} \leq ERPC_{r} \quad \forall r,t \tag{17}$$

D. Distribution Center

The mass balances for biofuel p and petroleum fuel f supply to the distribution center are defined by equations (18)-(23) and (24) defines the total blend produced from the distribution center. Ratio of biofuel supply to overall blend rate is given by equation (25).

$$\sum_{j,m} FJK_{jkmpt} + SBK_{kpt-1} = Bwk_{kt} + SBK_{kpt} \quad \forall k,p,t \tag{18}$$

$$inventDC_{kt} = \frac{Bwk_{kt}}{TOR_{k}^{k}} \quad \forall k,t \tag{19}$$

$$h^{min}.inventDC_{kt} \leq SPK_{k,p,t} \leq h^{max}.inventDC_{kt} \quad \forall k,p,t \tag{20}$$

$$\sum_{r,m} FRK_{rkmft} + SFK_{kft-1} = Fwk_{kt} + SFK_{kft} \quad \forall k,f,t \tag{21}$$

$$inventDC_{kt} = \frac{Fwk_{kt}}{TOR_{k}^{k}} \quad \forall k,t \tag{22}$$

$$h^{min}.Fwk_{kt} \leq SFK_{kft} \leq h^{max}.Fwk_{kt} \quad \forall k,f,t \tag{23}$$

$$Pwk_{kt} = Fwk_{kt} + Bwk_{kt} \quad \forall k,t \tag{24}$$

$$Pwk_{kt} = \frac{Bwk_{kt}}{OBR_{t}} \quad \forall k,t \tag{25}$$

Equation (26) sets the production limits for all blending stations k at period t and (27) ensures that new capacity $npcK_{kst}$ and capacity expansion (or contraction) $pcap_{kst}^{ke}$ is always added to current production capacity $Dprod_{kst}$.

$$Dprod_{kst} = Dprod_{kst-1} + npcK_{kst} + pcap_{kst}^{ke} \quad \forall k,s,t \tag{26}$$

$$\theta_{k}^{k}\left(EDCC_{k}^{k} + \sum_{s} Dprod_{kst}\right) \leq pwk_{kt} \leq EDCC_{k}^{k} + \sum_{s} Dprod_{kst} \quad \forall k,t \tag{27}$$

Equation (28)-(29) provide mass balance relationship between total production at DC whereas, flow of products to demand zones and actual sales. Equation (30) sets the limit of demand satisfaction.

$$pwk_{kt} = \sum_{d,m} FKD_{dkmt} \quad \forall k,t \tag{28}$$

$$\sum_{k,m} FKD_{dkmt} = Sales_{dt} \quad \forall d,t \tag{29}$$

$$Sales_{dt} \geq DEM_{dt} \quad \forall d,t \tag{30}$$

The new blending capacity $npcK_{kst}$ added to existing capacities for all sites k and size s is restricted by the discrete capacity sizes PC_{ks}^{DC} which can be selected from (31) and in like manner (32) restricts the expansion (contraction) capacity alternatives that can be added to existing plants. Equation (33) places practical limits on the number of plants that can be established in each period and this can be due to the availability of investment capital limitations.

$$npcK_{kst} \leq PC_{ks}^{DC}.y_{kst}^{k} \quad \forall k,s,t \tag{31}$$

$$pcap_{kst}^{ke} \leq \sum_{e} PC_{se}^{ke}.y_{kset}^{ke} \quad \forall k,s,t \tag{32}$$

$$\sum_{k} y_{kst}^{k} \leq N^{k} \quad \forall s,t \tag{33}$$

E. Logical Constraint

Response to variability in feedstock supply or demand satisfaction is handled by introducing flexibility to the supply chain capacity strategy. Inequalities (34)-(35) sets the condition that expansion (contraction) can only take place after plant is established and the plant closure also takes place upon plant establishment. Capacity expansion (contraction) can take place once as set by constraint (36)-(37). On the other hand (38)-(39) sets the condition for the closure of and expanded capacity when a plant is closed.

$$\sum_{e} y_{jqset}^{je} \leq \sum_{t' \in T: t' < T} y_{jqst'}^{j} - \sum_{t' \in T: t' > T} y_{jqst'}^{jc} \quad \forall j,q,s,t \tag{34}$$

$$\sum_{e} y_{kset}^{ke} \leq \sum_{t' \in T: t' < T} y_{kst'}^{k} - \sum_{t' \in T: t' > T} y_{kst'}^{kc} \quad \forall k,s,t \tag{35}$$

$$\sum_{et} y_{jqset}^{je} \leq 1 \quad \forall j,q,s \tag{36}$$

$$\sum_{et} y_{kset}^{ke} \leq 1 \quad \forall k,s \tag{37}$$

$$y_{jqst'}^{jc} = y_{jqst}^{jce} \; \forall jqst \tag{38}$$

$$y_{kst'}^{kc} = y_{kst}^{kce} \; \forall kst \tag{39}$$

F. Cost Constraint

The total investment costs of the entire supply chain, investment for harvesting sites, biorefinery and distribution center are given by (40)-(43) respectively

$$TCinv_{t} = \sum_{i} tic_{it}^{HS} + \sum_{j} tic_{jt}^{BP} + \sum_{k} tic_{kt}^{dc} \quad \forall t \tag{40}$$

$$tic_{it}^{HS} = \sum_{b}(FCI_{i} + VIC_{i}^{HS} * bhs_{bit})\, Y_{b,i,t}^{i} \quad \forall i,t \tag{41}$$

$$tic_{jt}^{BP} = \sum_{q,s}\left(FCI_{qs}^{j} Y_{jqst}^{j} + \sum_{e} FCI_{qse}^{je} Y_{jqset}^{je}\right) \quad \forall j,t \tag{42}$$

$$tic_{kt}^{DC} = \sum_{s}\left(FIC_{ks}^{k}\, Y_{kst}^{k} + \sum_{e} FIC_{kse}^{ke}\, Y_{kset}^{ke}\right) \quad \forall k,t \tag{43}$$

The associated closing costs TCC_t of the plants and distribution center is given by (44)

$$\mathrm{TCC}_t = \sum_{jqs} FBC_{qs} y_{jqst'}^{jc} + \sum_{ks} FDC_{ks} y_{kst'}^{kc} \quad \forall t \tag{44}$$

The processing and maintenance cost is calculated for all stages of the supply chain using equation (45).

$$C_t^{pr} = \sum_{b,i}\left(upc_{bt}^{HS}\mathrm{bharv}_{bit}\right) + \sum_{j,p,q}\left(upc_{qt}^{BP} pwj_{jpqt}\right) + \sum_{k}\left(upc_{kt}^{DC} pwk_{k,t}\right) \quad \forall t \tag{45}$$

Transportation cost of products and feedstock over all possible connections using all possible transportation modes in all time periods are also accounted for in equation. (46).

$$C_t^{TR} = \sum_m \Big(\sum_{b,i,j} UTC_{bmt}^{B} D_{ijm}^{ij} fij_{bijmt} + \sum_{p,j,k} UTC_{pmt}^{p} D_{jkm}^{jk} fjk_{jkmpt} + \sum_{p,j,l} UTC_{pmt}^{p} D_{jlm}^{jl} fjl_{jlmpt} + \sum_{p,j,l} UTC_{pmt}^{p} D_{dkm}^{dk} fkd_{dkmpt} + \sum_{f,k,r}(UTC_{f,m,t}^{f} D_{rkm}^{rk} FRK_{rkmft}) \Big) \ \forall t \tag{46}$$

Storage costs for the products and feedstock for the integrated supply chain is accounted for by equation 36.

$$C_t^{ST} = \sum_{b,j}\left(USC_{bjt}^{B} sbj_{b,j,t}\right) + \sum_{p,j}\left(USC_{pjt}^{Pj} spj_{p,j,t}\right) + \sum_{p,k}\left(USC_{pt}^{Pk} spk_{p,k,t}\right) \ \forall t \tag{47}$$

G. *Objective Function*

The objective function for this work is to minimize the total cost (TC) of the entire supply chain (48) which sums up the total costs in the establishment of this supply chain.

$$Minimize\ TC = \sum_t \left(TCinv_t + \mathrm{TCC}_t + C_t^{pr} + C_t^{tr} + C_t^{ST}\right) \tag{48}$$

IV. Case Study

A case study of northeast of Brazil is carried out where there is need for investment in ethanol biorefineries as a result of its insufficient production capacity [11]. Feedstock alternatives considered include corn and sugarcane as against the principal use of sugarcane for ethanol production. Biochemical conversion process is explored and proposed plant technology alternatives are corn Dry Mill ethanol, autonomous sugarcane ethanol and flex-mill (corn and sugarcane) technologies. Demand data for this case is obtained from historical data and projected according to historical average growth rate of fuel consumption [10]. 20 potential harvesting sites, 9 ethanol plant and blending location alternatives were considered in this case study to form the network. Furthermore 4 petroleum refineries within the region and 7 alternative export locations were also considered as part of the network. The table I below presents the demand and production data considered in this work which were sourced from [11], [12] respectively.

TABLE I: Average Ethanol Demand and Existing Production Capacity in the Northeast Region

Locations	*Average Demand (T/Yr)*	*Ethanol*	*Existing Capacity (T/Yr) sugarcane only*
Alagoas	132,368.02		386,932.70
Bahia	762,931.10		193,855.72
Ceará	405,115.00		-
Maranhão	226,024.96		116,705.72
Paraíba	232,030.79		301,398.00
Pernambuco	503,778.98		340,763.58
Piauí	159,524.09		29,571.72
Rio Grande do Norte	190,111.43		82,826.85
Sergipe	110,077.33		79,611.68

Source: [11], [12]

Table II. Further presents some input parameters used in the case study.

TABLE II: Model Parameters

Item	*Description*		*Unit*
Unit transport cost	• Corn	0.03[13]	$/t-km
	• Sugarcane	0.32[14]	
	• Ethanol	0.03[13]	
Unit ethanol processing cost	• Dry Mill Tech	132[15]	$/t
	• Autonomous Sugarcane Mill	100[16]	
	• Flexmill	108[16]	
Escalation factor	2		%
Interest rate	6		%
Ethanol Blends	E27	27	%
	E100	100	%
Overall Demand blend rate	0.35-0.38		%
Overall Demand growth rate	6		%

V. Results

The model was solved on an Asus S56C laptop with 4GB RAM and 1.70GHz CPU using the General Algebraic Modelling Systems (GAMS) version 23 environment, and CPLEX 11.2 solver. The model was solved in 955 seconds and the MIP dynamic search method was used by the solver in obtaining the solution. Optimality criterion was set to 1.47%

The results of the optimal supply chain configuration in fig. 1 below, shows that 3 harvesting sites H2 (Alagoas), H5 (Bahia) and H8 (Goias) were selected to produce the feedstocks for the plants as a result of the availability of large agricultural lands, high yield of feedstock (tons per hectare) and nearness from the biofuel production sites. Results also show that both corn (B2) and sugarcane (B1) were cultivated at H5 & H8 however only sugarcane is produced at H2. The dynamic nature of this supply chain makes it possible to have one site supplying feedstock to different biofuel plants in different periods.

We also observe that investment in plants takes place in all alternative locations which when compared to the existing production capacities in Table I, the only change is investments in Corn Dry Mill in Ceara where there was no exiting sugarcane ethanol production capacity. Although at the point of this submission, there wasn't publicly available data on capacities of existing blending stations within the Northeast region, it is also observed that for optimal demand satisfaction, investment in blending and distribution centers are located in K1(Sergipe), *k*2 (Rio Grande do Norte), *k*3 (Piaui), *k* (Pernambuco) and *k*8 (Bahia). Integration of the petroleum refinery to the supply chain also show that of the four (4) selected refineries within the region, two (2) are selected for optimal supply of gasoline to blending stations which is based on the relative distances to each blending center.

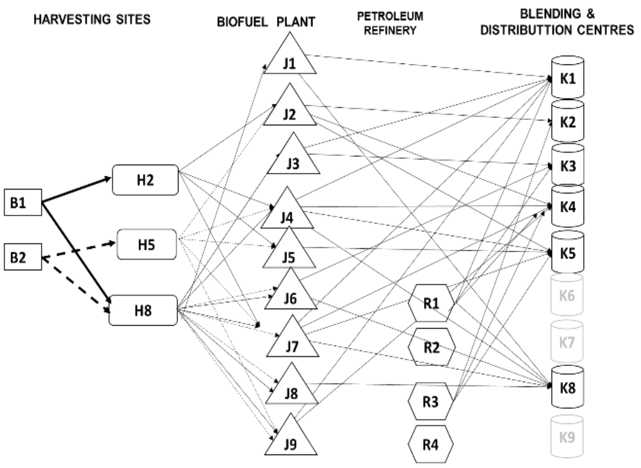

Fig. 1. Optimal supply chain Network.

Fig. 2 shows the evolution of biofuel plant Capacity upon implementation of plant dynamic capacity strategy. We observe that most plant investments were made in the first and second periods with capacity of 50 Ktons ethanol /yr (S1) and 150 Ktons ethanol /yr (S3). These plants capacities were expanded in subsequent periods due to the growing demand. All plants with capacity S1 were expanded to S3 to meet up with growing demand. This decisions are logical as the cost of establishing new plants are significantly higher than capacity expansions. We also observe that sugarcane ethanol production still plays significant role in the solution as about 50% of the new plants established are autonomous ethanol

Plants which is because of the lower cost of producing sugarcane ethanol in Brazil while 26% are Flex Mills owing to their higher production yields combining corn and ethanol. Capacity expansions take place in different periods to demonstrating the dynamism in this approach. Furthermore, as observed there was no capacity contraction or closure in the evolution, this because of the constant growth and deterministic nature of the demand.

Supply chain feasibility is dependent on several factors including feedstock availability, demand, price and costs, etc hence, sensitivity analysis was carried out on the model as shown in Table III.

TABLE III: SCENARIOS FOR SENSITIVITY ANALYSIS

Scenario	*Description*
1	10% decrease in annual demand
2	10% decrease in annual biomass availability
3	15% increase in annual demand
4	5% increase I overall blend rate

Results of the sensitivity analysis as summarized in Table IV. Indicates no significant changes in number of plants with decrease in available biomass however, number of plants with technology Q1 increase whereas Q2 decreases by 1 plant and Q3 remains same, this may imply that in a case of biomass scarcity autonomous sugarcane ethanol plants and flex plants would be preferred for investments over Corn Dry Mill ethanol plants.

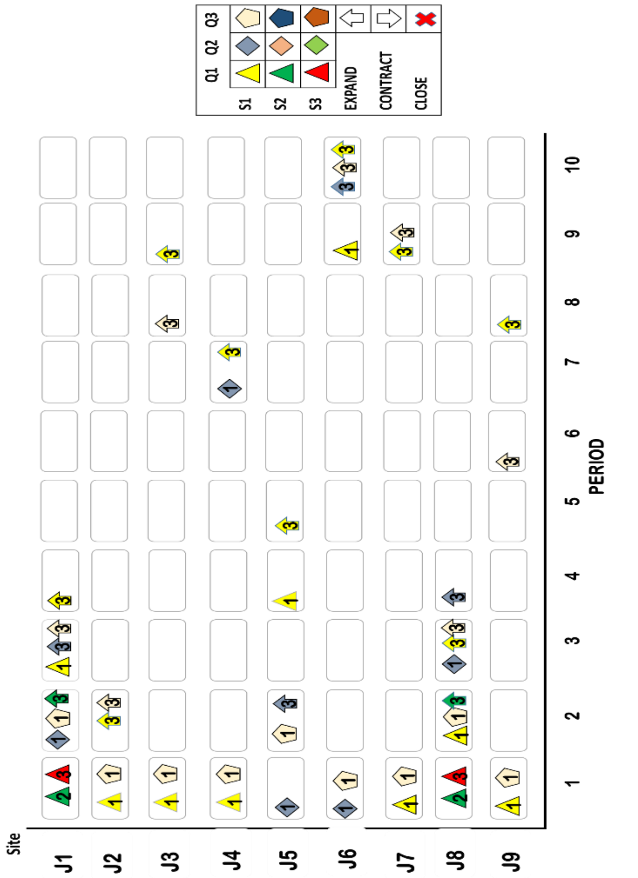

Fig. 2. Evolution of Biofuel plant capacity.

Similarly, a 10% decrease in annual demand shows a decrease in total number of plants arising from decreases in Q1 and Q3 whereas a 15% increase in annual demand results in an increase total number of plants favoring more investments in technologies Q1 and Q3. Summarily, the sensitivity analysis of this case study show that investments in autonomous sugarcane ethanol plants will play a large role in in ensuring market equalization of fuel consumption in Brazil and flex plants and corn Dry mill ethanol plants will also make significant contributions.

This current article doesn't yet incorporate the seasonality of these feedstocks, profitability of the entire supply which could validate the work done by [17], environmental objectives which can further add realism to the model and aid strategic investment decisions.

TABLE IV: RESULTS OBTAINED FROM SENSITIVITY ANALYSIS

	Technology									
	Q1			**Q2**			**Q3**			
Scenario	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**Total**
Base case	9	2	2	6	0	1	7	0	0	27
Scenario 1	9	1	1	7	0	0	5	0	0	23
Scenario 2	10	2	2	5	0	1	7	0	0	27
Scenario 3	9	3	4	4	0	3	9	0	0	32
Scenario 4	10	3	2	5	0	2	7	0	0	29

VI. CONCLUSION

In this present paper, a strategic planning model for integrated biofuel and petroleum supply chains is studied. The optimization problem is formulated as a MILP whose objective is to minimize the total cost of the entire supply chain with the implementation of a dynamic capacity strategic for opening, expansion, contraction and closing decisions.

Three types of technologies were considered for biofuel production: Autonomous Sugarcane-ethanol plant, Corn Dry Mill Plant and Flex mills where, two transportation modes, discrete capacity sizes for new plants and expansion (contraction) decisions. The model was developed on the basis of the Brazilian ethanol supply chain. Results from the model supplies the optimal supply chain configuration, investment locations and capacities, and evolution of plant capacity over time. The model is proposed as a tool for investment decision making in supply planning and design.

A case study using the Brazilian ethanol supply chain is carried out considering existing ethanol plants in the northeast, petroleum refineries and distribution centers in the region to equalize the fuel deficit met by imports. Results show that investment in Autonomous sugarcane biorefineries plays a significant role in meeting demand while the flex and Corn Dry Mills also plays significant roles.

APPENDIX

Nomenclature

Indices

B	Biomass feedstock
D	demand zones
E	Set of capacity change alternatives
I	harvesting sites
J	biofuel plants
K	Blending & Distribution centres
L	international markets
M	Transport modes

Parameters

AB_{bit}	Available biomass at harvesting site I in period t
bharv_{bit}	Biomass harvest from site I in period t
BY_{bi}	biomass b yield at harvesting site i tons T per hectare Tons/ha
DEM_{dt}	Demand at retail centers at time t tons per year Tons/year
D_{kdm}	distance between distribution and retail centers using transport mode m, km
D_{ijm}	distance between harvesting sites and biofuel plants using transport mode m, km
D_{jkm}	distance between biofuel plants and distribution centers using transport mode m, km
$EBPC_{j,q}^{j}$	Existing biofuel plant capacity j using technology q Tons/year
$EFPC_{r}^{r}$	Existing petroleum refinery production capacity Tons/year
$EDCC_{k}^{k}$	Existing distribution center production capacity Tons/year
FBC_{qs}	Closing cost of biorefinery of technology q and size s, $
FCI_{i}	fixed capital investment for harvesting sites $
FDC_{ks}	Closing cost of distribution center k of size s, $
FIC_{qs}^{BP}	fixed capital investments for biofuel plants $
FIC_{qse}^{BPe}	fixed capital investments for biofuel plants expansion $
FIC_{s}^{DC}	fixed investment cost for distribution centres k with capacity s ,$
FIC_{se}^{DCe}	fixed investment cost for expansion (contraction) distribution centres k with capacity s ,$
LA_{bi}	available land for biomass cultivation in harvesting sites i ,hectares ha
$\theta_{j,q}^{j}$	minimum production level allowed in biofuel plant j with tech q ,%
θ_{k}^{k}	minimum production level allowed in blending station k, %
$Bprod_{j,q,t}$	production capacity of biofuel plant j using technology q with capacity s ,Tons/year
$PC^{BP}{}_{qs}$	Discrete capacities sizes for technology q
$PC_{k,s}^{DC}$	Discrete capacities sizes for blending stations with size s
pc_{qse}^{be}	Discrete capacity size alternatives e for new plants with technology q and size e
$Dprod_{kst}$	production capacity of Blending plant k with capacity s ,Tons/year
TOR_{b}^{b}	turnover ratio of biomass in time period ,days/replenishment
TOR_{j}^{j}	turnover ratio of biofuel plant in time period ,days/replenishment
TOR_{k}^{k}	turnover ratio of distribution center in time period t, days/replenishment
UTC_{bmt}	unit storage cost of biomass b at plant j at time t, $/Ton
UTC_{pmt}	Unit transport cost of product p using transport mode m at time t,($/ton)/km
VIC_{i}^{HS}	variable investment cost on harvesting site i ,$/ton
$u_{(b,q)}^{p}$	biofuel to biomass conversion ratio, ton Biofuel/ton biomass
upc_{it}^{HS}	unit production cost of biomass at harvesting site i at time t,$/ton
upc_{jt}^{BP}	unit production cost of biofuel at refinery j using technology q at time t,$/ton
upc_{kt}^{DC}	unit production cost of blends at blending station k, at time t,$/ton
$\beta ioFlim_{b,t}$	percentage of biomass allocated for biofuel,%

Binary variables

$y^{i}{}_{bit}$	decision variable if a harvesting site is selected or not,
y_{jqst}^{j}	Decision variable if biofuel plant j, with technology q with capacity s is built at time t
y_{jqset}^{je}	Decision variable for capacity expansion of new plant
y_{kst}^{k}	Decision variable if distribution center k with capacity s is built at time t
y_{kset}^{ke}	Decision variable for capacity expansion of new blending station
$y_{kst'}^{kc}$	Decision variable for closure of new blending station
$y_{jqst'}^{jc}$	Decision variable for closure of new biofuel plant

Continuous variables

C_{t}^{pr}	total processing cost of fuels $
C_{t}^{ST}	total storage cost,$/year
C_{t}^{TR}	total transportation cost raw materials and products,$/year
$TCinv_{t}$	Total investment cost,,$/year
$b\omega j_{b,j,q,t}$	biomass b consumed at plant j using technology q at time t, tons/year
$Bwk_{k,t}$	Biofuel consumed in blending at site k in period t
FIJ_{bijmt}	flow of biomass from harvesting site i to plant j, tons/year
FJk_{jkmpt}	flow of biofuel from refineries j to distribution centers k, tons/year
FJL_{jlmpt}	flow of ethanol from plant j to export terminal l, tons/year
FKD_{dkmt}	flow of fuel blend p from distribution centers k to retail center, tons/year
FRK_{rkmft}	flow of fossil fuel from refineries & terminals l to distribution centers k, tons/year
$inventBP_{jpt}$	biofuel p inventory at plant j at time t, tons/replenishment
$npcJ_{jqst}$	new biofuel plant j with capacity s and technology q addition at time t, tons per year
$npcK_{kst}$	new distribution center addition k with capacity s at time t, tons per year
OBR_{t}	Overall blending ratio of biofuel product p to fossil fuel f,

	ton Biofuel/ton fossil fuel at time t
$pcap_{jqst}^{je}$	Capacity expansion (or contraction) for new plant j, with technology q and size s at period t
$pcap_{kst}^{ke}$	Capacity expansion (or contraction) for new blending k, size s at period t
pwj_{jpqt}	production of biofuel p from plant j using technology q at time t, tons per year
$pwk_{k,t}$	Production of fuel blends at blending center k at time t
$Sales_{dt}$	sales of product µ at retail center d at time t, tons per year
$SBJ_{b,j,t?}$	storage of biomass b at plant j at time t, tons per year
$SPJ_{p,j,t?}$	storage of biofuel product p at plant j at time t, tons per year
tic_{t}^{BP}	total investment cost for biofuel plants,$
tic_{t}^{dc}	total investment cost for distribution centers,$
tic_{it}^{HS}	total investment cost for harvesting sites,$
	Total supply chain cost
Scalars	
h^{max}	factor for estimating max capacity for storage
h^{min}	factor for estimating min capacity for storage
HL	Harvest loss

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Acknowledgment

The authors gratefully acknowledge the Petroleum Technology Development Fund (PTDF), Nigeria for the financial support of this work.

References

[1] M. R. M. Wellisch, G. Jungmeier, A. Karbowski, and M. K. Patel, "Biorefinery systems – Potential contributors to sustainable," *Biofuels, Bioprod. Biorefining Innov. a Sustain. Econ.*, vol. 4, no. 275–286, pp. 275–286, 2010.

[2] H. An, W. E. Wilhelm, and S. W. Searcy, "Biofuel and petroleum-based fuel supply chain research: A literature review," *Biomass and Bioenergy*, vol. 35, no. 9, Pergamon, pp. 3763–3774, Oct. 2011.

[3] S. A. Hosseini, A. Abedpour, and M. Yu, *Multi-scale Process and Supply Chain Modelling: From Feedstock to Process and Products*, vol. 31, no. July, Elsevier B.V., 2012.

[4] F. E. Andersen, M. S. Díaz, and I. E. Grossmann, "Multiscale strategic planning model for the design of integrated ethanol and gasoline supply chain," *AIChE J.*, vol. 59, no. 12, pp. 4655–4672, Dec. 2013.

[5] A. E. Duarte, W. A. Sarache, and Y. J. Costa, "A facility-location model for biofuel plants: Applications in the Colombian context," *Energy*, vol. 72, pp. 476–483, Aug. 2014.

[6] A. Duarte, W. Sarache, and Y. Costa, "Biofuel supply chain design from coffee cut stem under environmental analysis," *Energy*, vol. 100, pp. 321–331, Apr. 2016.

[7] K. Tong, M. J. Gleeson, G. Rong, and F. You, "Optimal design of advanced drop-in hydrocarbon biofuel supply chain integrating with existing petroleum refineries under uncertainty," *Biomass and Bioenergy*, vol. 60, pp. 108–120, Jan. 2014.

[8] B. Ivanov and S. Stoyanov, "A mathematical model formulation for the design of an integrated biodiesel-petroleum diesel blends system," *Energy*, vol. 99, pp. 221–236, Mar. 2016.

[9] M. M. M. Chávez, W. Sarache, and Y. Costa, "Towards a comprehensive model of a biofuel supply chain optimization from coffee crop residues," *Transp. Res. Part E Logist. Transp. Rev.*, vol. 116, pp. 136–162, Aug. 2018.

[10] ANP. (2019). Dados estatísticos. [Online]. Available: http://www.anp.gov.br/dados-estatisticos

[11] ANP, *Fuel Production and Supply Opportunities in Brazil*, 2017.

[12] Unica. (2019). Unicadata. [Online]. Available: www.unica.com.br/unicadata

[13] SIFRECA. (2020). Etanol - Sifreca | SISTEMA DE INFORMAÇÕES DE FRETES - Departamento de Economia, Administração e Sociologia Escola Superior de Agricultura 'Luiz de Queiroz' (ESALQ/USP). [Online]. Available: https://sifreca.esalq.usp.br/en/mercado/milho

[14] D. Khatiwada, S. Leduc, S. Silveira, and I. McCallum, "Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil," *Renew. Energy*, vol. 85, pp. 371–386, Jan. 2016.

[15] A. Johanns. (2020). Prices and profitability models | agricultural marketing resource center. [Online]. Available: https://www.agmrc.org/renewable-energy/prices-and-profitability-models

[16] C. Iglesias and J. P. Sesmero, "Economic analysis of supplementing sugarcane with corn for ethanol production in Brazil: A case study in uberaba," *Bioenergy Res.*, vol. 8, no. 2, pp. 627–643, 2015.

[17] A. Kostin, D. H. Macowski, J. M. T. A. Pietrobelli, G. Guillén-Gosálbez, L. Jiménez, and M. A. S. S. Ravagnani, "Optimization-based approach for maximizing profitability of bioethanol supply chain in Brazil," *Comput. Chem. Eng.*, vol. 115, pp. 121–132, Jul. 2018.

Aba Michael M. graduated from the Federal University of Technology Minna (2012) with bachelor degree in engineering (B.Eng.). He is currently undergoing his masters program at the Polytechnic School of the Universidade de Sao Paulo to obtain a master of Science (M.Sc.) degree.

He has worked as a research analyst in the food industry and also a technical analyst on diverse oil and Gas projects. His current research is in the energy and environment area.

He was awarded NNPC/MPN undergraduate scholarship in 2008/2009 and currently holds the Petroleum Technology Development Fund (PTDF) Nigeria scholarship award. His Profile can be found on the link http://lattes.cnpq.br/8181941243657883

Galo A.C Le Roux obtained his B.Sc. (1987) and M.Sc. (1991) in chemical engineering from the Department of Chemical Engineering of the Polytechnic School of the University of São Paulo and Ph.D. in process engineering from Institute National Polytechnique de Toulouse, France (1995).

He works as a professor at the Universidade de Sao Paulo and also serves as the president of the Associaçao Brasileira de Engenharia Quimica (ABEQ) till date. His Research focus is on modeling, simulation, optimization and process control, with emphasis in parameter estimation and system identification. He has supervised several projects and served as referee to several scientific journals. A compendium of publications he has authored and co-authored can be found in the link http://lattes.cnpq.br/9084088181088883.