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Strategic planning of sustainable integrated biofuel and petroleum fuel supply chains

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This dissertation is dedicated to God, my family and friends for all the support and encouragement all through my Master's Program.

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ABSTRACT

Petroleum has been the major source of meeting the world's energy and chemical needs but rising energy demand, dwindling petroleum resources and climate change have led to an energy revolution resulting in the development of alternative fuels to replace fossil-derived energy products. Biofuel is one of the viable solutions that is increasingly becoming part of the energy mix of many nations whose market has become established by biofuel policies and regulations. However, investments in biofuel supply chains can be expensive and several supply chain models have been developed to demonstrate its cost-effectiveness or profitability without considering integrating with existing petroleum infrastructure. Also, seldom considered is the impact of demand fluctuations on capacity allocation and changes over time. Hence, this work presents a multi-period multiscale strategic planning model for policy-decision makers and which is an integrated biofuel and petroleum supply chain which composes a superstructure that combines the components of the biofuel and petroleum supply chain. The model presented is a Mixed Integer Linear Programming (MILP) model used to make strategic and tactical decisions for biorefineries and distribution centers under environmental considerations to ensure sustainability. Furthermore, a dynamic capacity strategy is incorporated which allows for flexibility in the capacity allocation and location decisions in response to demand fluctuations over time. The model is applied to a case study in the Northeast of Brazil under the *RenovaBio* program where investments in biorefineries are required to overcome the production deficit in the region and eliminate import. Results of the case study carried out produced an optimal facility configuration of biorefineries and distribution centers, the evolution of capacities over time, capacity utilization profile, material flows and inventories, carbon credit and emissions profile from the network while maximizing the net present value of the supply chain. Results also show significant investments in corn dry mill and flex mill plants. This contribution shows that biorefinery supply chains modelled to incorporate the interactions petroleum fuel supply chain can provide insights that would not be possible with only biofuel supply chain models. It is shown that mathematical programming offers useful tools for biorefinery supply chain studies.

Keywords: Strategic Planning, Mixed Integer Linear Programming (MILP), Biofuels, Integrated Biofuel-Petroleum Supply chain, Supply chain.

RESUMO

O petróleo tem sido a principal fonte de atendimento às necessidades energéticas e não energéticas do mundo, mas a crescente demanda por energia, a diminuição dos recursos petrolíferos e as mudanças climáticas levaram a uma revolução energética, resultando no desenvolvimento de combustíveis alternativos para substituir produtos energéticos derivados de combustíveis fósseis. . Os biocombustíveis são uma das soluções viáveis e estão se tornando cada vez mais parte do mix de energia de muitas nações cujo mercado foi estabelecido por políticas e regulamentações especificos. No entanto, os investimentos em cadeias de suprimentos de biocombustíveis podem ser elevados e vários modelos de cadeia de suprimentos tem sido desenvolvidos para estuda relação custo-benefício ou lucratividade sem considerar a integração com a infraestrutura de petróleo existente. Além disso, raramente é considerado o impacto das flutuações da demanda na alocação de capacidade e mudanças ao longo do tempo. Portanto, este trabalho apresenta um modelo de planejamento estratégico multiescala e multiperíodo para uma cadeia de suprimentos integrada que compõe uma superestrutura que combina os componentes da cadeia de suprimentos de biocombustíveis e petróleo. O modelo apresentado é um modelo de Programação Linear Inteira Mista (MILP) usado para tomar decisões estratégicas e táticas para biorrefinarias e centros de distribuição sob considerações ambientais a fim de garantir a sustentabilidade. Além disso, uma estratégia dinâmica de capacidade é incorporada, o que permite flexibilidade nas decisões de alocação e localização de capacidade em resposta às flutuações da demanda ao longo do tempo. O modelo é aplicado a um estudo de caso no Nordeste do Brasil, no âmbito do programa RenovaBio, no qual são necessários investimentos em biorrefinarias para superar o déficit de produção na região e eliminar as importações. Os resultados do estudo de caso realizado produziram uma configuração ideal das instalações das biorrefinarias e centros de distribuição, evolução das capacidades ao longo do tempo, perfil de utilização da capacidade, fluxos e balanços materiais, crédito de carbono e perfil de emissões da rede, maximizando o valor presente líquido da cadeia de suprimentos . Os resultados também mostram investimentos significativos nas usinas de etanol de milho e flex. Esta contribuição mostra que as cadeias de suprimentos de biorrefinaria modeladas incorporando as interações da cadeia de suprimentos de combustível de petróleo podem fornecer informações que não seriam possíveis apenas com os modelos de cadeias de suprimentos de biocombustíveis. É mostrado que a programação matemática oferece ferramentas úteis para estudos da cadeia de suprimentos de biorrefinaria.

Palavras-chave: Planejamento Estratégico, Programação Linear Inteira Mista (MILP), Biocombustíveis, Cadeia de suprimentos integrada de biocombustíveis e petróleo, Cadeia de suprimentos.

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LIST OF ABBREVIATIONS AND ACRONYMS

ATR Asset Turnover Ratio

CH_4 Methane

CO_2e Carbon dioxide equivalent

DC Distribution Center

DSC Dynamic Capacity Strategy

FCFF Free Cash Flow to Firm

GHG Green House Gases

MILP Mixed Integer Linear Programming

MINLP Mixed Non-Integer Linear Programming

RC Retail Center

SKV Stakeholder Value

TRAD Traditional Capacity Strategy

LIST OF SYMBOLS

Sets

b set of Biomass feedstocks

d set of demand zones

f set of petroleum fuel products

i set of harvesting sites

j set of biofuel plants

k set of Blending & Distribution centers

m set of Transport modes

p set of biofuel products

q set of Biofuel processing technologies

r set of existing petroleum refineries

s set of plant capacity size levels

t set of periods

τ_q	The seasonal operational pattern of biorefineries
A_b	Available biomass b at harvesting site i in period t, *t/period*
B_b^{li}	Percentage of biomass allocated for sustainable biofuel production, %
B_b	biomass b yield at harvesting site i, *t/ha*
D_d	Demand at retail centers at time t, *t/period*
D_{dl}^{d}	Distance between distribution and Demand centers using transport mode m, *km*
D_{ii}^{i}	distance between harvesting sites i and biofuel plants j using transport mode m, *km*
D_{jk}^{j}	distance between biofuel plants j and distribution centers k using transportation means m, *km*
E_{j}^{j}	Existing biofuel plant capacity j using technology q, *t/period*
E_{k}^{k}	Existing production capacity at the distribution center k, *t/period*
E_b^H	Emission factor associated with feedstock cultivation, *tCO2e/t*
E_b^q	Emission factors associated with biomass processing at biorefinery, *tCO2e/t*
E_m	Emission factors for transport mode m, *tCO2e/t-km*
E_b^q	Emission credit associated with feedstock type b, *tCO2e/t*
E_r^r	Existing petroleum refinery production capacity, *t/period*
F_q	Fixed cost for closing biorefinery, *US$*
F_q	Fixed cost for closing biorefinery capacity expansion, *US$*
F_q^j	fixed capital investments for biofuel plants *US$*
F_q^j	The fixed investment cost for biorefinery capacity expansion (contraction), *US$*
$F_{k,s}^k$	the fixed investment cost for distribution centers k with capacity s, *US$*

$F \quad {}^{k}_{k}$ the fixed investment cost for distribution centers capacity expansion (contraction) with capacity s, *US$*

$F \quad {}_{k}$ Fixed cost of closing blending and distribution center, *US$*

$F \quad {}_{k}$ Fixed cost of closing blending and distribution center capacity expansion, *US$*

$L \ {}_{b}$ available land for biomass cultivation in harvesting sites i, hectares *ha*

$L \quad {}_{k}$ Fuel price in domestic market k in period t, *US$/t ethanol*

$N \quad {}_{t}$ Nationally determined emission reduction target, *tCO2e/period*

O_{j} minimum percentage of production allowed in ethanol plant j with tech q, %

$O \quad {}_{t}$ Overall biofuel blend rate in period t, %

$P \ {}^{j}_{q}$ Discrete Production capacity of biofuel plant j using technology q with capacity s, *t/period*

$P \ {}^{j}_{q}$ Discrete expansion/contraction capacity e for existing biofuel plant using technology q with a current capacity s, *t/period*

$P \ {}^{k}_{k}$ The production capacity of the distribution center with capacity s*, t/period*

$P \ {}^{k}_{s}$ Discrete expansion/contraction capacity e for existing distribution center with a current capacity s , *t/period*

$S \quad {}_{b}$ Feedstock seasonality

$T \quad {}^{b}_{b}$ turnover ratio of biomass feedstock, *days/replenishment*

$T \quad {}_{t}$ Emission reduction target for fuel distributors, *tCO_2e/period*

$T \quad {}^{j}_{j}$ turnover ratio of biofuel plant, *days/replenishment*

$T \quad {}^{k}_{k}$ turnover ratio of the distribution center, *days/replenishment*

$\mu_{b,q}$ biofuel to biomass conversion ratio, *t Biofuel/ t biomass*

$U \quad {}^{i}_{b}$ the unit production cost of biomass b at time t, *US$/t-period*

$U \quad {}^{j}_{b}$ Unit biomass processing cost at biofuel plant in period t, *US$/t-period*

$U \quad {}^{k}_{k}$ Unit blending cost at site k in period t, *US$/t-period*

$U \quad {}^{r}_{r}$ Unit refining petroleum refining cost, *US$/t-period*

$U \quad {}^{B}_{b}$ nit storage cost of biomass b at plant j at time t, *US$/t-period*

$U \quad {}^{P}_{p}$ unit storage cost of product p at biofuel center j at time t*, US$/t-period*

$U \quad {}^{P}_{p}$ unit storage cost of product p at distribution center k at time t, *US$/t-period*

$U \quad {}^{f}_{f}$ unit storage cost of product f at distribution center k at time t, *US$/t-period*

$U \ C^{B}_{b}$ Unit transport cost of biomass b using transport mode m at time t, *US$/t-km*

$U \ C^{P}_{p}$ Unit transport cost of product p using transport mode m at time t, *US$/t-km*

$U \quad {}^{f}_{f,m,t}$ Unit transport cost of product f using transport mode m at time t, *US$/t-km*

Binary Variables

y^{i}_{b} Decision variable if a harvesting site is selected or not,

y^{j}_{j} Decision variable if biofuel plant j, with technology q with capacity s, is built at time t or not

y^{j}_{j} Decision variable if biofuel plant j, with technology q with capacity s, is expanded (contracted) to size e at time t or not

y^{j}_{j} Decision variable if biofuel plant j, with technology q with capacity s, is closed at time t or not

y^{j}_{j} Decision variable if biofuel plant expansion j, with technology q with capacity s, is closed at time t or not

y_k^k	decision variable if the distribution center with capacity s is built at time t or not
y_k^k	decision variable if distribution center with capacity s is expanded (contracted) at time t or not
y_k^k	decision variable if the distribution center with capacity s is closed at time t or not
y_k^k	decision variable if distribution center expansion (contraction) with capacity e is built at time t or not

Scalars

E^k	Emission factor associated with blending and distribution, *tCO_2e/t*
E^r	Emission factor associated with petroleum refining, *tCO_2e/t*
E^p	Emission factor associated with the combustion of biofuel, *tCO_2e/t*
E^f	Emission factor associated with the combustion of petroleum fuel, *tCO_2e/t*
H^m	the factor for estimating maximum storage capacity
H^m	the factor for estimating minimum storage capacity
B	Facility Investment budget, *US$*
θ	Tax rate, %
N	Number of periods
P	Carbon credit price, *US$/t*
I_l	Interest rate, %
S	Salvage value
UDP	Demand shortage cost *US$/t*

Continuous Variables

bhs_b	biomass b harvesting from the site I in period t, *t biomass/ period*
b_j	Total biofuel plant production capacity *t/period*
c_t^P	Total processing cost of fuels, *US$/period*
c_t^S	Total storage cost of feedstock and products, *US$/period*
c_t^T	Total transportation cost for feedstock and products, *US$/period*
c_t	Carbon credit due to fuel distributor, *tCO2e/period*
c_t	Net cash flow, *US$/period*
d_t	Depreciation
d_k	Total distribution center production capacity *t/period*
q_b^i	the flow of biomass b from harvesting site i to plant j using transport mode m, *t/period*
q_{jk}^j	the flow of biofuel from refineries j to distribution centers k, using transport mode m, *t/period*
q_{dl}^k	the flow of fuel blend p from distribution centers k to the retail center, using transport mode m, *t/period*
q_{rk}^r	the flow of fossil fuel from refineries & terminals r to distribution centers k, using transport mode m, *t/period*
f_r	product output of refinery r at time t, *t/period*
f_t	Fractional depreciable capital at period t, *US$/period*
il_b^b	Minimum biomass inventory requirement at the plant, , *t/replenishment*
il_j^E	Minimum Biofuel p inventory at plant j at time t, *t/replenishment*

il_k^D	Minimum Blend product p inventory at the distribution center at time t, *t/replenishment-period*
n_t	Net earnings, *t/period*
n_j^j	New biofuel plant j with capacity s and technology q at time t, *t/period*
n_k^k	New distribution center addition k with capacity s at time t, *t/period*
NPV	Net Present Value, *US$*
p_j^j	Biofuel plant expansion/contraction capacity*, tons/period*
p_k^k	Distribution/blending center expansion/contraction capacity*, tons/period*
r_t	Revenues, *US$/period*
$s_{d,t}$	Sales of product at retail center d at period t, *t/period*
s_b^j	storage of biomass b at plant j at time t, *t/period*
s_k^k	Inventory of petroleum derivative f at distribution center k at time t, *t/period*
s_j^j	storage of biofuel product p at plant j at time t, *t/period*
s_k^k	Inventory of biofuel p at distribution center k at time t, *t/period*
t_t^{in}	Total investment cost, *US$/period*
t_t	Total closing cost, *US$/period*
t_b^b	Total emissions from feedstock cultivation, *tCO_2e/period*
t_q^b	Total emissions from the biorefining process, *tCO_2e/period*
t_t^d	Total emissions from petroleum refining and fuel blending, *tCO_2e/period*
t_t	Total emissions from fuel combustion, *tCO_2e/period*
t_t	Total supply chain emissions, *tCO_2e/period*
t_t^p	Total emission from processing activities, *tCO_2e/period*
t_t^t	Total emissions for transportation activities, *tCO_2e/period*
t_j^B	total investment cost for biofuel plants, *US$/period*
ti_k^D	total investment cost for distribution centers, *US$/period*
u_t	Penalty for unmet demand, *US$/period*
u_d	Unmet demand, *t/period*
w_b^{i-b}	biomass b consumed at plant j using technology q in period t, *t/period*
w_j^{o-j}	Production of biofuel p from plant j using technology q at time t, *t/period*
w_k^{o-k}	Production of fuel blend from blending center k at period t, *t/period*
w_k^{i-k}	Petroleum fuel consumed at Distribution center k in period t, *t/period*
w_k^{o-k}	biofuel consumed at Distribution center k in period t, *t/period*

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1 Introduction

Petroleum has been the major feedstock for the production of energy and non-energy products and chemicals for several decades with its demand majorly driven by fuel consumption, however, rising energy demand, dwindling petroleum resources and climate change have resulted in an energy revolution leading to progressive research and development of the bio-economy. The bio-economy is a bio-based economy which proposes to replace fossil-based chemicals and products with biomass-derived chemicals and products and this lies at the core of the development of the bio-economy. This is because a bio-based economy promises less use of non-renewable resource like petroleum, coal etc, and reduction in greenhouse gas (GHG) emissions caused by man's energy use, creation of new employment opportunities, and fostering innovation using cleaner and more efficient technologies (Wellisch et al., 2010; Jong et al., 2011)..

At the center of the bioeconomy is the Biorefinery which is analogous to a petroleum refinery. It processes biomass into a spectrum of products such as energy, biofuels; bioethanol, biodiesel, biogasoline, etc and co-products; biopolymers, succinic acid etc. It can be fed by primary (e.g. harvested biomass), secondary (e.g. process residues), or tertiary biomass feedstocks (e.g. post-consumer wastes or residues) (Wellisch et al., 2010; Jong et al., 2011).

The emergence of biorefineries around the world are of various types and sizes dependent on final product type, product demand, available feedstock, public acceptance and polices. Several classifications have been made for biorefineries based on technology: conventional and advanced biorefineries; first, second, and third-generation biorefineries, feedstock type: whole crop biorefineries (WCBRs), oleo-chemical biorefineries, lignocellulosic feedstock biorefineries, green biorefineries, and marine biorefineries and type of intermediate product/platform: syngas platform biorefineries, sugar platform biorefineries and type of conversion processes applied: thermochemical biorefineries, biochemical biorefineries, two platform concept biorefineries. The primary purpose of establishing a biorefinery is sustainability and its primary product is the biofuel, which is aimed at substituting its fossil fuel counterpart in line with global initiatives and mandates to reduce GHG emissions from transport and energy through fuel switching (De Jong; Jungmeier, 2015).

However, Biorefineries are only a part of an entire supply chain and to achieve their sustainability, a value chain approach which ensures energy access and affordability must be taken into consideration by planning and designing these biorefineries with respect to their supply chains. This involves all activities involved in making strategic decisions ranging from feedstock selection to actual production and consumption by the end-user (Hosseini; Abedpour; Yu, 2012; De Jong; Jungmeier, 2015; Palmeros Parada; Osseweijer; Posada Duque, 2017).

Furthermore, the new regulations on GHGs reduction mandate the inclusion of biofuels in fuel matrix which implicitly implies reduction on petroleum fuel consumption and probable shut down of some facilities in the long-run. This arises an opportunity for integration of biofuel supply chain with existing petroleum-based systems which has the potential of reduction of infrastructural costs and logistics costs because of the codependences. This approach is seldom considered in biofuel supply chain planning and design (Pack, 2007; An; Wilhelm; Searcy, 2011). Hence, a new approach to biofuel supply chain management (BSCM) is required to sustainably leverage integration opportunities with the petroleum supply chain.

1.1 Background

The biofuel supply chain consists of a network of harvesting sites, gathering centers, biorefineries, storage facilities, distribution and demand centers.

At the harvesting sites, the biomass is cultivated in regions that offer suitable climates, soil conditions, water supply and growing seasons of sufficient duration to enable good yields. Upon maturation, the biomass is harvested and must typically be pre-processed to reduce moisture content and particle size before it is stored at the gathering centers or processed at a bio-refinery to produce biofuel. The level of moisture that is acceptable depends on the conversion method utilized. Smaller particles enhance the speed of conversion. Stored biomass continues to degrade until converted. After conversion, biofuel may share some aspects of petroleum-based fuels blending and distribution systems and to a large extent, compete with petroleum-based fuels in terms of both price and demand, however, government regulations ensure an increasing market for it (An; Wilhelm; Searcy, 2011).

Similarly, the petroleum supply chain comprises of the upstream, midstream and downstream sectors. At the upstream activities involving crude oil exploration, extraction and storage at terminals are carried out. This crude oil is then transported via pipelines, ships and barges to refineries for processing to an assorted set of products such as gasoline, diesel, kerosene etc which is the midstream activity. Distribution and Sales to the final consumer describe the downstream sector. The petroleum supply chain is well developed around the world (Andersen; Díaz; Grossmann, 2013).

Although biofuel production technology development has received a lot of focus in recent times, design of a robust, reliable and sustainable biofuel supply chain is essential to deliver competitive end products to the end-user. This requires biofuel supply chain planning and management. Biofuel supply chain planning involves planning decisions at different levels: Strategic, Tactical and Operational which are dependent on time and duration. (Awudu; Zhang, 2012).

Most Biofuel Supply chain designs in the literature focus on upstream and midstream opportunities for planning and management of biorefineries without seeking out opportunities for integration with existing petroleum infrastructure, however, as predicted by An; Wilhelm and Searcy, (2011b) biofuel demand will be more predictable due to the regulations on Green House Gases (GHG) by many countries which have 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 except for integrated hydrocarbon biofuel and petroleum supply chains as was studied by Russell, Dawn M; Ruamsook, Kusumal; Thomchick, (2009); Andersen; Díaz; Grossmann, (2013); Tong et al., (2014a, 2014b); Tong; You; Rong, (2014).

1.1.1 Supply Chain planning

Planning as part of supply chain management is focused on short, medium and long term decisions which may involve operational planning, acquisitions, consolidations and capacity analysis with a strategic focus. It supports decision-making by identifying potential alternatives and making the best decisions according to the planner´s objectives (Kallrath, 2002; Ahumada; Villalobos, 2009).

According to a review carried out by Hosseini, Abedpour and Yu, (2012); Yue, You and Snyder, (2014), most research works on bio-economy development has focused on supply chain design mainly involving transportation network design and biorefinery facility locations, however, fewer studies incorporate tactical and operational planning in supply chain models. Inclusion of tactical and operational planning in supply chain models will yield higher resolution and realism in supply chain design. This could also be challenging without any prior assumptions about the structure of the Supply Chain Network.

1.1.2 Supply Chain Planning Decision levels

As discussed above, biorefinery planning cuts across 3 decision levels characterized by the length of time in consideration i.e. long, medium or short term. These decision levels are discussed in detail in the following section.

i. Strategic decision level

Strategic decisions are long-term planning decisions spanning over one (1) year involving significant financial investments which cannot be altered in the short or medium term. Such decisions include the selection of the type of refinery, facility location, capacity or size of refinery energy production technologies, supply chain and network configuration, biomass allocation among refineries, supply and demand contracts, and ensuring sustainability. Four objective functions such as minimize overall costs, maximize overall profit, maximize net present value, minimize risk on investment are the most commonly evaluated metrics in at this decision level (Awudu; Zhang, 2012; Yue; You; Snyder, 2014; Ahn et al., 2015; BA; Prins; Prodhon, 2016).

Facility location and capacity allocation are two (2) dynamic strategic decisions which require careful analysis to incorporate a capacity strategy that accounts for demand fluctuations. A capacity strategy defines the overall scale of operation, number and size of sites between which capacity is distributed, activities allocated to each site, time-dependent changes in capacity levels, and scale of changes and location of sites (Chávez; Sarache; Costa, 2018).

There are two capacity strategies applied in making strategic decisions: Traditional and Dynamic strategy. The traditional capacity strategy is the commonly applied strategy in supply chain designs which assumes opening of facilities in the initial period and remains unchanged throughout the planning period while the dynamic strategy allows for the opening of facilities in any period and also the expansion or contraction and closure of facilities within the planning period (Chávez; Sarache; Costa, 2018). The dynamic strategy is seldom considered in strategic planning models hence will be applied in this work.

ii. Tactical decision level

At the tactical level, medium-term decisions spanning from weeks to a few months are applied to a multi-period horizon usually limited by the strategic decisions. Such decisions include harvesting, feedstock sourcing, production decisions, scheduling, choice of transportation modes, Inventory and logistical policies and contracts, and planning process definition. An example is feedstock supply planning which may involve the amount to harvest in each farm and each period, the number of vehicles to be purchased (fleet size), and the definition of safety stock levels (Awudu; Zhang, 2012; BA; Prins; Prodhon, 2016; Bairamzadeh; Saidi-Mehrabad; Pishvaee, 2018).

iii. Operational decision level

At the operational level, decision making involves short-term (Day-to-day) activities and can be adjusted frequently in correspondence to the current external and internal conditions such as day-to-day inventory control in biofuel inventory planning and vehicle planning and scheduling in fleet management. Harvest operation timing in a day, scheduling, fulfilling customers demand and vehicle routing are typical examples of operational decisions that are made (Yue; You; Snyder, 2014; Ahn et al., 2015; BA; Prins; Prodhon, 2016; Bairamzadeh; Saidi-Mehrabad; Pishvaee, 2018).

1.2 Sustainability in supply chain planning

Renewability of bio-resources used in biorefineries has often been misunderstood to imply the sustainability of biorefineries. While the former may have environmental benefits, sustainability is not limited to the environmental dimension of but encompasses health, economic and social dimensions as well which should be considered in the value chain assessment. Hence, in designing or assessing biorefinery projects performance evaluations concerning sustainability to determine the severity of the project on the different aspects of sustainability is necessary. The sustainability concept as defined by the Brundtland document (World Commission on Environment Development, 1987) is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This has become an important point of focus for the development of bioeconomies and design of biorefineries of the future. (Wellisch et al., 2010; Palmeros Parada; Osseweijer; Posada Duque, 2017).

Survey results of 300 firms around the world reported by Chaabane; Ramudhin; Paquet, 2011 stated that 50% of the surveyed firms have plans to redesign their supply chains adopting the sustainability concept while 80% of firms are required to comply with new environmental regulations, hence, organizations around the world are faced with new realities of ensuring the sustainability of their businesses as corporate social responsibility or as a legal requirement (Palmeros Parada; Osseweijer; Posada Duque, 2017).

There is a lot of work at national and international level in developing sustainability-based principles, criteria, and indicators to guide industry, government and society sustainable bioenergy development. Approaches such as foresighting and strategic sustainable development fosters sustainability planning at the industry level (Wellisch et al., 2010).

1.2.1 Sustainability dimensions

Sustainability concept cuts across three (3) dimensions: Economic, Environmental and Social dimensions. These should all be considered in project performance evaluations for optimal results. These are discussed in the following sections.

i. Economic dimension

The economic dimension is one of the most researched and used sustainability indicator. It involves the evaluation of costs, profits, investment value (i.e. NPV) and margins of projects. It is usually aimed at determining the profitability of the biorefinery design or comparing biorefinery alternatives in terms of cost for production of a product over a period (Palmeros Parada; Osseweijer; Posada Duque, 2017).

ii. Environmental dimension

The environmental dimension is the most evaluated among all dimensions whether as a single indicator or combined with other dimensions. This has been included in biorefinery designs through methods that indicate the expected environmental impacts of the project. The lifecycle assessment (LCA) approach is usually applied in this dimension and common metric evaluated include Global Warming Potential (GWP), Abiotic Depletion (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) or summer smog, and Terrestrial Ecotoxicity Potential (TETP). The key factors used to evaluate environmental sustainability include feedstock type, the technologies and their respective conversion and energy efficiencies; types of manufactured products and associated emissions; what products are substituted by the bioproducts, and bioproduct use and disposal at the end of life (Wellisch et al., 2010; Santoyo-Castelazo; Azapagic, 2014; Palmeros PARADA; Osseweijer; Posada Duque, 2017).

iii. Social Dimension

The social dimension is the least explored dimension when compared to the environmental and economic dimensions. This is because the metrics used are not so established and easily measured. Some of the metrics include food and energy security, health effects, job creation, etc (Schaidle; Moline; Savage, 2011; Palmeros Parada; Osseweijer; Posada Duque, 2017).

1.2.2 Multi-scale modelling of biorefineries

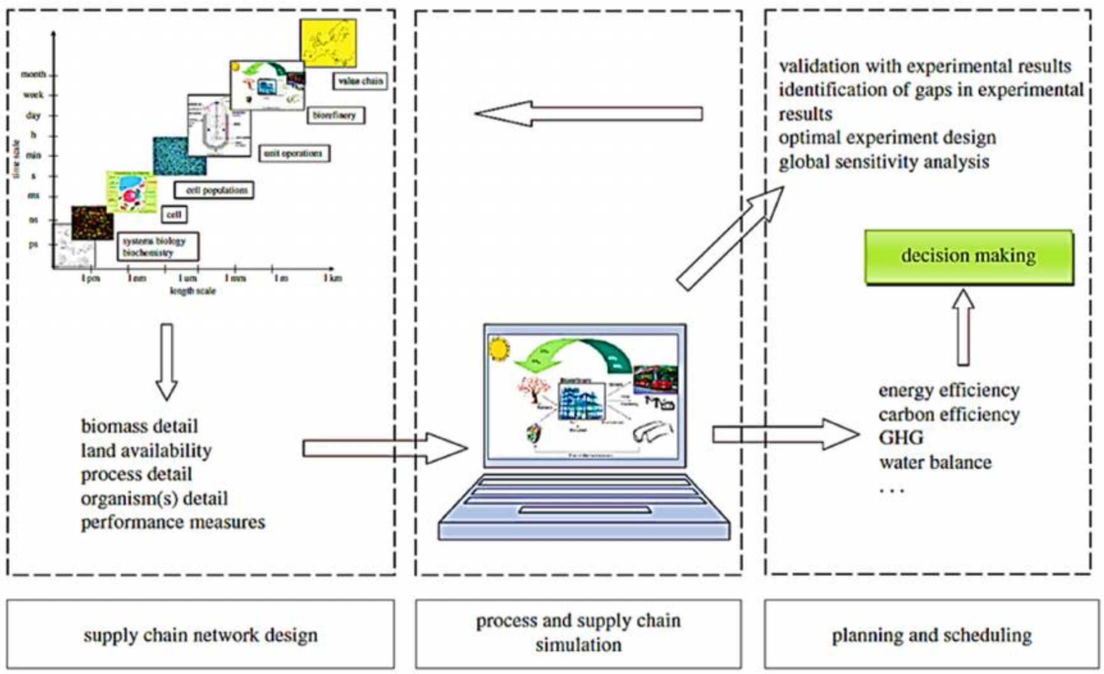
Planning and Sustainability assessment of process systems requires a holistic view of the problem and valuation of impacts and interactions between different temporal and spatial scales of the system sequentially or simultaneously. This requires a new approach that incorporates models across multiple scales (micro to macro). This concept has led to the development of the multiscale engineering concept, which has been applied in different areas of engineering especially in the energy and environment focus research areas (Floudas et al., 2016).

Recent contributions by applying this approach present reduced model frameworks (coarse models) that help in solving complexly detailed (fine) models through the application of nonlinear optimization techniques. This modelling approach also provides an avenue for costs reduction and as new technologies of biomass conversions are developed, this approach can aid the modelling of biofuel production techniques, process synthesis strategies for optimal bio-refineries and supply chains (Floudas et al., 2016).

Hosseini and Shah, (2011) posited that the main problems relating to the ethanol market do not lie in the variation in demand as has been the main focus of many pieces of research, however, the focus should be directed to finding the best network configurations that integrate different feedstocks to meet demand year-round with emphasis on efficiency and economics of bioenergy networks. The authors also proposed the use of conceptual process models from the molecular level up to the unit operations and then an overall process consideration of the supply chain model. This implies considering the process as a set of black boxes (meta-models) instead of a black box whose results are used in the global network design

A diagrammatic representation of the interactions between scales and how it can pave the way to answer holistic supply chain offering higher resolutions and greater realism is shown in Figure 1.

Figure 1. How multi-scale modelling can pave the way to answer holistic supply chain questions



Source: (Hosseini; Shah, 2011)

The concept of multi-scale optimization is relatively new and it is gradually being accepted in process systems and supply chain designs. The discussion on bioenergy developments is not left out in this discussion. Some works of literature that adopted this concept are summarized going forward.

Zhuang, Bakshi and Herrgård, (2013) considered various scales associated with the production of biochemical and proposed a multiscale modelling framework which involves the application of simulations and prediction of lower scale models to parameterize higher-level models and in turn the higher-level models provide constraints to lower-level models. The entire process model can then be summarized into a single stoichiometric model which is representative of the biochemical industry and a single link in the flow network model. Then this can be connected to existing chemical industry models and subsequently economic and ecological models. However, there are certain challenges with this approach: some processes may have unknown parameters and also uncertainties in overall process parameters that may affect the integration of ecological models with chemical industry models.

As has been laid out in the previous sections, planning initiatives ought to consider single or more decision levels in biorefinery supply chain design while implementing sustainability metrics and the higher the integration of decision levels, the more realistic the design. Therefore, managers must decide on the following questions as stated by Pack, (2007)

1. Which feedstocks to purchase,
2. When, from where, and how much to purchase of each feedstock,
3. Where, how much, and how long to store each feedstock, and product
4. Where, when, how many, and how big are facilities
5. How much of and when to produce each product,
6. How much of and where to distribute each product, and
7. How to plan for additional production capacity.

While also considering

8. Integration point with petroleum fuel supply chain
9. What biorefinery technologies should be adopted
10. Sustainability performance evaluation

Question #1: Which feedstocks should be purchased?

This decision considers biorefinery feedstock procurement which is heavily influenced by conversion technology configuration, whether it can process single or multiple feedstocks. Thus any research effort that discusses feedstock procurement should consider approaches and methodologies appropriate to single or multiple potential feedstock types.

Question #2: When, from where, and how much feedstock should be purchased?

Seasonality of feedstock impacts on the availability of feedstock in different periods and locations. This also impacts on the quantity available as a result of varying yields. Production levels and inventory also influence feedstock procurement at the Biorefinery site. Furthermore, factors such as the distance of harvesting sites from biorefineries, available land and yield also influence the origin of feedstock at the plant while demand volatility, product price, feedstock scarcity, feedstock price, and other factors including storage impact on feedstock purchase. Hence these should be considered in decision making.

Question #3: Where, how much, and how long to store each feedstock and product?

Inventory levels are usually related to the feedstock consumption rate, purchase quantity, price of feedstock, cost of storage, and rate of spoilage/perishability, end-product price and inventory duration.

Feedstock seasonality and perishability determines its storage duration to enable constant Biorefinery production in periods of low or no availability. This is also dependent on the economics of storage at Biorefinery, harvesting site or gathering centers whichever is more favorable.

Question #4: Where, when, how many, and how big are the facilities?

This decision is highly complex and is influenced by factors such as regulatory stipulations, access to employees, political sensitivity, long term competitive strategy, financial health, adversity to investment risk, etc. Many of these factors are unquantifiable therefore only quantifiable factors are considered in the system design.

Timing and location of facilities are impacted by product demand growth, feedstock availability, the economic viability of access to distribution channels and feedstock and product transportation costs. These may necessitate the opening or closing of facilities, hence, should be evaluated to provide a more realistic investment plan.

The density of Biorefineries in a location is also an important decision as this implies economically favorable conditions to meet demand. The density of biorefineries should be just enough to meet demand but not so many to increase competition for feedstock. The size of biorefineries is also important as this affects economies of scale, demand for feedstock.

Question #5: How much of and when to produce each product?

Biorefinery production levels are determined by product demand and prices, feedstock availability and associated costs, minimum production limits, production schedules, available product and feedstock inventory at the plant and distribution centers.

Question #6: How much of and where to distribute each product?

Products are allocated among distribution centers and finally customers over time with a bid to maximize profit. Variation in product prices and distributions costs by location implies product should be allocated to the demand locations that offer the highest prices and in closest proximity.

Question #7: How to plan for additional production capacity?

As demand grows, additional capacity will be added, similarly, a contraction of demand may also imply contraction in capacities and in case permanent demand destruction, closure is carried out. Hence, this decision should be made to determine the capacity strategy to be applied in responding to significant changes in demand. These decisions include opening a new facility, expanding an existing facility, contraction existing facility and closure of the facility. This decision is affected by demand, but also by feedstock availability and many of the other factors described above.

Question #8: integration point with petroleum fuel supply chain

As biofuels are substitutionary fuels for their petroleum fuel counterparts, this decision involves choosing the point of integration between petroleum fuel and biofuel supply chains. This is determined by desired end products, demand, price and configuration of existing petroleum infrastructure.

Question #9: what Biorefinery technologies should be adopted?

Biorefinery technologies to be adopted depend on availability and type of feedstock in the region, desired end products, available technologies and their maturation, level of investment in research and scale-up facilities, public acceptance, and policies that support the transition to a greener and more efficient hybrid economy.

Question #10: sustainability performance evaluation

In addressing this decision, the following should be taken into consideration: what specific sustainability goals are we aiming to achieve? Are we strictly interested in reducing GHG emissions? Do we need to create new jobs and support rural development? Do we anticipate land scarcity and want to derive maximum environmental benefits from biomass use per unit of land? Do we want to reduce our use of non-renewable resources to provide greater energy security or to provide future generations with equal opportunities? Answers to these questions are key to sustainable biorefinery design as they will affect the decisions made concerning the selection of products, technologies, and configurations.

1.3 Research Motivation

Long term planning of bioenergy projects involves high capital investments which require economic evaluation strategies to determine the optimal investment strategy to adopt in planning decisions. Furthermore, the need to capitalize on existing petroleum infrastructure promises a viable path to reducing investment costs in establishing biorefinery projects/ supply chains and in meeting national biofuel mandates. Hence, a multiscale strategic planning model that considers the integration of existing petroleum and new bioenergy infrastructure presents a tool for policy decision making and optimization of biorefinery planning and design considering their environmental impacts.

1.4 Research Objectives

Given the benefits of an integrated supply chain, the main objective of this work is to model an integrated strategic planning model to a biofuel and petroleum supply chain under sustainability considerations to demonstrate the potential economic benefits from integration with downstream petroleum supply chain and also incorporate environmental sustainability in both supply chains concerning national and international climate change emissions targets.

This model will have a dynamic framework implying that supply chain configurations regarding feedstock type and source, facility capacity, location & technology may vary with time. Also, it will incorporate strategic and tactical decisions while also applying the dynamic capacity strategy to examine the impact of capacity evolution to demand. Environmental impact in terms of the global warming potential will also be evaluated under the nationally determined CO_2 emission reduction targets. The inclusion of feedstock seasonality will also help to address issues about feedstock and product inventory management in the supply chain and apply the forgoing could lead to the development of sustainable and realistic integrated biofuel supply chain design tool.

Not only does this work help in the strategic design of integrated biofuel and petroleum supply chains but also helps to answer the questions in Pack, (2007);

The scope of this work will cover the economic optimization of integrated ethanol and gasoline supply chain, implementation of dynamic capacity strategy, evaluation of Global Warming Potential (GWP) of the supply chain, Case study of Strategic planning of biorefineries in Brazil using Corn and Sugarcane as feedstock and considering three ethanol production pathways and finally carry out a Sensitivity analysis.

1.5 Literature Review

Researchers have been addressing biofuel and biomass supply chain planning and design from several perspectives such as agricultural engineering, agronomy, forestry, operational research, transportation research, energy research and chemical engineering perspectives. Although there are several publications on this subject matter to date, only a few consider the integration of biorefining systems with petroleum supply systems (Pack, 2007; Sharma et al., 2013). The reviews of literature in this section will be discussed concerning their modelling approach, entities, biomass types, and end-products, decision level, integration with petroleum supply chain, capacity strategy and quantitative performance measures.

Biomass availability is dependent on factors such as seasonality and location. This poses the need for optimal planning of the location of plants in a distributed network and as bioenergy efforts are targeted towards sustainability, effective usage of natural resources becomes necessary. Consequently, for a Mexico case study to produce ethanol and biodiesel from lignocellulosic residues, jatropha and palm oil, López-Díaz et al., (2017) developed a Mixed Integer Non-Linear Programming (MINLP) optimization model which incorporated optimal facility locations concerning feedstock cultivation sites and a watershed under environmental constraints. The supply chain comprised of feedstock source, biorefineries and markets with no petroleum supply chain integration. Only strategic decisions were considered and traditional capacity strategy was applied. The objective of this work is to maximize the net annual profit. This work did not evaluate the environmental impact of this approach.

Gargalo et al., (2017) developed a multi-objective decision-making framework for the optimal design and planning of glycerol biorefinery supply chains to produce polyhydroxy butyrate (PHB), lactic acid (LA), succinic acid (SA), 1,2-propanediol (1,2-PDO), 1,3-propanediol,(1,3-PDO), acrolein (Acro), and epichlorohydrin (Epi), from crude glycerol, considering economic and environmental objectives under uncertainties. The supply chain structure consisted of feedstock suppliers, biorefining plant and markets for the final product. Decisions considered in this model involve strategic decisions such as location, number, technology and capacities of Biorefinery facilities while considering product inventory as a tactical decision. Traditional Facility capacity strategy was also applied. Both deterministic and stochastic modelling approaches were deployed to formulate a multiproduct, multi-period, and multistage Mixed-Integer Linear Programming (MILP) and applying Lifecycle assessment for environmental impact assessment. Quantitative measures include maximization of the Net Present Value (NPV) and environmental impact performance by measuring Greenhouse Gas evaluation. However, this work was lacking in integration with the petroleum supply chain.

Furthermore, a MILP supply chain design and optimization model were developed by Domínguez-García et al., (2017) addressing the synergy of satisfying the demand for aviation fuels and hydrogen using biomass and fossil materials to produce cost-effective and environmentally friendly solutions in Mexico. An integrated biofuel and petroleum supply chain was considered comprising feedstock sources/suppliers for biomass and crude oil, Biorefineries for the conversion of biomass to aviation fuel and biohydrogen which is supplied to a petroleum refinery, petroleum refinery for the production of fossil aviation fuel and markets: Domestic and international. Only strategic decisions were considered related to the best conversion pathway, raw materials and distribution network for aviation fuel in Mexico. Traditional Facility capacity strategy considered was applied. Quantitative measures analyzed include economic benefit and GHG emissions while the model was deterministic.

Andersen; Díaz; Grossmann, (2013) developed a strategic planning model for an integrated ethanol and gasoline supply chain network composed of a superstructure that combines the components of both supply chains and different means of transportation. The components consist of harvesting sites, Biorefinery, blending and distribution center, petroleum refineries and retail stations. The model is a multiscale multi-period MILP design problem which considers strategic and tactical decisions such as facility location, capacity, technology, retrofit scheduling transportation and inventory management. The traditional capacity strategy was applied to both Biorefinery and blending station capacity. Aggregated and detailed Models were formulated to determine investment hotspots for gas stations and sites for retrofits with blending pumps respectively to minimize the total cost of the network. The model is deterministic. However, the environmental sustainability of the supply chain is not considered in this work.

Duarte; Sarache; Costa, (2014) formulated a MILP model which considered plant facility location, plant number and material flows as decision variables in a Colombian context. The authors focused on the strategic planning of biorefineries to produce bioethanol from coffee stems residue to maximize the economic benefit (profit). Although, assuming a steady flow of petroleum fuel with a strict blend recipe to meet domestic and international biofuel demands, No Petroleum supply chain was included. This work does not also consider the environmental impacts of the supply chain nor tactical decisions such as transportation and inventory management. The foregoing was further updated to a multi-objective optimization problem in Duarte; Sarache; Costa, (2016) where the facility location problem was carried out under environmental considerations. However, it does not include the upstream echelon of the biofuel supply chain and the petroleum supply chain is not considered in environmental analysis, hence petroleum upstream and midstream GHG emissions are neglected.

A buildup on a publication by Duarte; Sarache; Costa, (2016) by Chávez; Sarache; Costa, (2018) produced a comprehensive supply chain model for biofuel produced from coffee residues (stems, pulp & mucilage). In this work, the authors developed a multi-objective MILP model for the bioethanol supply chain incorporating strategic decisions such as facility location, capacity, transportation, feedstock seasonality and inventory management. This considers a dynamic capacity strategy that involves capacity opening, expansion, contraction and closing decisions, adding distinction from traditional capacity strategies which only involves opening and seldom closing decisions. The supply chain is composed of the harvesting sites, feedstock gathering centers, biorefiney and blending stations but does not include petroleum supply chain. This multiscale modelling and dynamic capacity strategy adds more realism to the system while ensuring compliance with long-term and short-term goals. The ε-constraint optimization method was applied to the objectives of maximizing NPV (economic objective) and number of jobs created by the supply chain (social objective) while minimizing environmental impact (environmental objective).

Tong et al., (2014a) formulated a MILP model that addresses the optimal design and strategic planning of advanced drop-in hydrocarbon biofuel supply chain integrating with existing petroleum refineries under pricing and quantity uncertainties. The Authors present an innovative approach towards integration of biofuel and petroleum supply chain where 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. The supply chain comprised of harvesting zones, biomass pre-conversion plants, biorefinery intermediate products, upgrading plants, conventional biorefinery, petroleum refinery, distribution center and gas station. The proposed model is a multiscale multi-period planning model used to solve deterministic and probabilistic cases. The objective is to minimize the total annualized cost however environmental objectives were not considered to evaluate the GHG emissions of this process or profitability of deploying this strategy.

Ivanov; Stoyanov, (2016) formulated an MILP model for the strategic planning of an IBSC (integrated biodiesel supply chain) using total annualized cost and total life cycle GHG emissions as economic and environmental quantitative measurement criteria, respectively. The authors included crop rotation conditions to assure the supply of biological feedstock and took into account infrastructure compatibility, 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. The authors, however, consider only strategic decisions without the inclusion of inventory management along the supply chain which has the potential of regulating the frequency of feedstock/product reorder and avert disruption in supply or demand satisfaction as the case may be. The traditional capacity strategy was applied in defining capacity additions.

The strategic planning of Microalgae Biomass Biodiesel Supply Chain Network (MBBSCN) is also studied by Ahn et al., (2015) to determine the optimal configuration between CO_2 source (supply point) and sink (demand point). The authors incorporated an innovative utilization of CO_2 wastes from power plants collected in Carbon capture and storage (CCS) systems and wastewater from treatment plants for the production of microalgae which is further processed to biodiesel at the Biorefinery. The superstructure consisted of feedstock facilities, biorefineries and demand zones and only strategic decisions were considered in this work. A multi-period MILP model that minimizes the total cost of the biodiesel network is formulated to determine the optimal configuration of links among sources (feedstock fields for biomass growth) and sinks (fuel stations for demand cities). However, the work is limited as it does not evaluate the sustainability performance of the network and integrate the petroleum supply chain.

Santibañez-Aguilar et al., (2014) carried out the optimal planning of multiproduct biorefineries using Mexico as a case study to optimize three objectives; economic, environmental and social objectives. The model considers a multi-objective, multi-period MILP problem which is aimed at maximizing net profit and number of jobs created while minimizing environmental impact. In this study, the Jobs and Economic Development Impact methodology, the IMPLAN model and information reported by different governmental institutions were used to account for the number of jobs generated for each stage and product in the entire life cycle. Also a linear relationship between the number of jobs and production levels was assumed to determine the number of jobs created.

Chaabane; Ramudhin; Paquet, (2011) also developed a multi-objective mixed-integer linear programming (MO-MILP) optimization framework for supply chain design that incorporates both environmental and economic objectives (reduction of GHG emissions and logistics cost, respectively) while considering the interactions with the carbon market. The model considers both internal strategic mechanisms and carbon leverages to provide decision-makers with the most cost-effective options for meeting with regulations. However, this work is limited as it considers a single carbon price not taking into consideration volatility and lacks the inclusion of multiple periods and life cycle stages.

Santibañez-Aguilar et al., (2011) formulated a mathematical model for the optimal selection of feedstock, processing technology and set of products which maximized profit and minimized environmental impact. A multi-objective optimization model is employed for a case study in central Mexico. The ECO-99 indicator is applied in determining the environmental impact based on lifecycle analysis of resources, processing technologies and products.

Sharma; Sarker; Romagnoli, (2011) developed a decision and analysis framework to describe the design and operation of a fledgling biorefinery with economic, environmental and social objectives simultaneously. The constructed model is a multi-period planning model with financial considerations (maximizing stakeholder value). The free cash flow to firm (FCFF) method is used in the enterprise evaluation and the work considers four (4) biomass types namely stover, straw, switchgrass and miscanthus and 2 biodiesel feedstock such as soybean and waste oil for the production of ethanol, biodiesel and other value added products (Co-products). The model framework is designed to be flexible enough to allow opportunities for integration of technologies and products where CO_2 emissions and wastes streams are utilized for the production of co-products such as Succinic acid and 1,3-propanediol that provide an opportunity to improve profitability.

A multi-layered decision support tool was developed and implemented by Geraili; Salas; Romagnoli, (2016) considering strategic, tactical and operational tasks. A decomposition strategy was proposed in this work that combined net present value optimization with rigorous non-linear process simulation and process level stochastic optimization. This is applied to a multiproduct lignocellulosic biorefinery where a stochastic MILP is developed to optimize the strategic decision level and the stochastic optimization coupled with simulation to optimize the operational decision level. The results obtained from this work showed a difference from those obtained from literature attributed to the non-linear modelling and optimization strategies used to achieve a greater degree of resolution and realism.

Kostin et al., (2018) carried out a nationwide supply chain design to optimize the profitability of sugarcane ethanol in Brazil. In this work, the supply chain comprised of the cultivation areas, production plants, storage facilities and markets and Seven technologies or configurations for the production of sugar and ethanol to meet domestic and international market demands were considered. The optimization approach adopted is an MILP that considers both strategic and tactical decisions including inventory management, facility location, capacities, transportation etc. Traditional capacity strategy was applied for making the capacity decision making for biorefineries and product storage facilities. However, this work was limited in considering other feedstock alternatives such as corn and other plant configurations such as the flex mills. It also did not take the environmental impact of the supply chain into consideration especially with the nationally determined emission reduction targets.

Khatiwada et al., (2016) carried out a techno-economic optimization analysis to complement existing research studies in Brazil which are focused on economic and environmental benefits of biorefineries at plant level by examining the costs and emissions of the entire supply chain. The authors considered the use of sugarcane agricultural residues and agro-industrial co-product (bagasse) for second-generation (2G) ethanol and energy production in Sao Paulo state. The authors also considered technological improvements of existing mills while investigating the impact of technological change, policy drivers/incentives, and market volatilities. To do this, a mixed-integer linear program (MILP) was applied to optimize the choice of technology for producing energy products and services in sugarcane biorefineries. This model minimizes the cost of the biofuel supply chain including sugarcane production (agricultural practices), feedstock transportation, biomass processing, biofuel transportation and carbon emission costs. However, this work is limited in the scope of the supply chain and does not consider other feedstock alternatives and technologies that could increase production at minimum cost.

1.5.1 Summary of literature review

A significant amount of research has been done in developing biofuel supply chain models considering strategic decisions such as capacity planning, number of plants, location, technology and production pathway selection, supplier selection for biorefineries, and tactical decisions such as biomass storage, transportation, production planning, harvest scheduling, etc. However, there is a paucity of models that integrate petroleum supply chain and apply the multiscale approach. Also, feedstock seasonality is seldom considered and the capacity planning strategy commonly used has been the traditional capacity strategy, that assumes a constant facility capacity from inception and throughout the planning horizon, Hence, a more realistic strategy that includes feedstock seasonality and adds dynamism to facility capacities, making them responsive to demand fluctuations in new supply chain models, and inclusion of sustainability metrics that evaluate the performance of integrated biofuel and petroleum supply chains could facilitate the development of more realistic decision-making tools.

The remaining sections of this dissertation are arranged as thus:

Chapter 2: Mathematical model formulation

Chapter 3: Data collection, and parameter definition

Chapter 4: Computer implementation, results and discussion

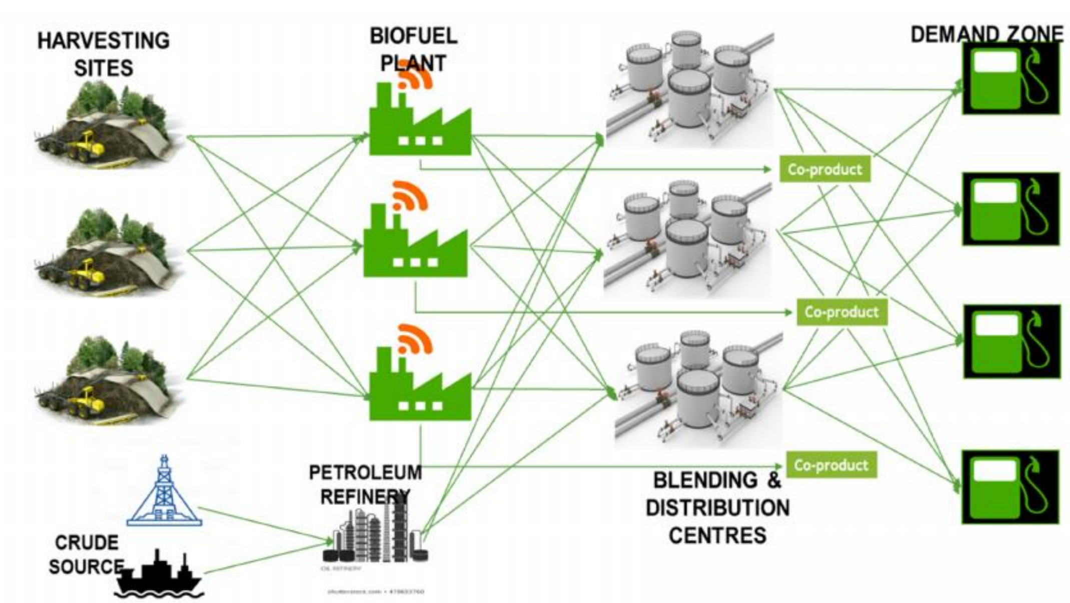
Chapter 5: Conclusion and recommendations

2 Mathematical Model Formulation

The mathematical model described in the following sections is a mixed-integer linear programming model for an integrated multisite and multimarket supply chain superstructure for Ethanol and gasoline developed by Andersen; Díaz; Grossmann, (2013) as shown in Figure 2. It represents an aggregated model which takes into consideration both existing and planned capacities for ethanol production and distribution points with respect to the location of existing petroleum refineries. Due to its multiscale nature, a bi-level decomposition algorithm where the upper-level problem makes the long-term decisions and the lower level one performs the short-term decisions is adopted.

The model is further extended in this work, to account for dynamism in plant capacities over time as a result of variation in demand and also includes environmental impact evaluation and implementation of a simplified *Renovabio* carbon trading scheme. Feedstock production patterns with respect to seasonality are also considered. Other modifications also include a change in economic objective to account for profitability of the supply chain and consideration of an overall blend rate instead of the disaggregated approach done in the original work.

Figure 2. Integrated Petroleum and Biofuel supply chain



Source: Author

2.1 System scope

The system comprises of two (2) supply chains; the Biofuel and Petroleum fuel supply chains. Integrated biofuel supply chains as shown in Figure 2 consists of the harvestings sites where the biomass cultivation takes place after which it is transported to the biofuel plants where this biomass is transformed to bioproducts which include biofuels, energy, chemicals, resins etc. Technologies applied to this transformation could be Biochemical, Thermochemical or hybrid which combines the best attributes of both biochemical and thermochemical technologies. The produced biofuel is then further transported to the petroleum blending and distribution site where blending operations are performed according to national mandates or regulations.

As shown in Figure 2, petroleum supply chain integration also covers the supply of crude oil to refineries which could be sourced locally or imported, also refined products can be sourced to augment local refinery supply in the case of short supply. These refined products are then delivered through pipelines, rail, barges, or trucks to fuel terminals or blending/distribution centers for blend production and finally distribution to gas stations for actual sales.

Biofuels targeted for the export market are also delivered from the production plants to the transference terminals.

The decisions that must be made for an optimally integrated supply chain include:

- Material flows between harvesting site (HS) and plants
- Choice of feedstocks
- Biofuel production location and capacity
- Biorefinery Technology selection
- Interconnections between plant and distribution centers
- Product and feedstock inventory management
- Location and capacity of distribution centers (DC)
- Material flows between petroleum refineries and distribution centers

- Capacity utilization of plants and distribution centers
- Blend sales and demand satisfaction at retail centers
- Transportation logistics of feedstocks and products

2.2 Harvesting sites

The equations (1)-(3) describe the biomass production constraints at the harvesting sites. Equation (1) describes the mass balance and limits the biomass production that will be available A_{b} for biofuel production with the parameter B_{b}^{li} that limits allowable biomass harvest for biofuel production. The available biomass is determined by the product of Available land L_{b} for agricultural production and biomass yield B_{b} also which also takes into consideration harvest losses H. S_{b} defines the seasonal harvest pattern for feedstocks. The available biomass parameter is pre-calculated and fed to the model.

Equation (2) states that if biomass *b* is available for harvest from harvesting site *i* ($y_b^i = 1$), then the amount that can be harvested bhs_b cannot exceed the amount of biomass available A_{b} from harvesting *i*.

$$A_{b} = L_{b} B_{b} B_{b}^{li} (1 - H) S_{b} \qquad \forall b, i, t \tag{1}$$

$$bhs_b \leq A_{b} \, y_b^i \qquad \forall b, i, t \tag{2}$$

The mass balance of biomass flow from the harvesting site *i* to the ethanol plants *j* is also described by equation (3) stating that the mass of biomass harvest bhs_b must equal the flowrate q_{b}^{i} of feedstock *b* delivered from site *i* to plant *j* using transportation mode *m* at period *t*.

$$bhs_b = \sum_{j,m} q_{b}^{i} \qquad \forall b, i, t \tag{3}$$

2.3 Biofuel Production Plant

The mass balance of biomass at the production plant is described by equations (4)-(6). Equation (4) state that the sum of biomass *b* delivered q_{b}^{i} to plant *j* and stored inventory from the previous period $s_{b\,-1}^{j}$ must equal the sum of biomass *b* consumed

w_b^{i-b} at the plant, j using technology q and the inventory s_b^{j} in the current period. Equation (5) defines the inventory level il_b^b of feedstock b which is the minimum amount between replenishments required to provide plants with feedstock while Equation (6), on the other hand, provides upper and lower bounds for the biomass inventory levels at the site j based on the factors H^m and H^m .

$$\sum_{i,m} q_b^{i} + s_{b\ -1}^{j} = \sum_q w_b^{i-b} + s_b^{j} \quad \forall b, j, t \tag{4}$$

$$il_b^b = \frac{\sum_q w_b^{i-b}}{T_b^b} \ \forall b, j, t \tag{5}$$

$$H^m \ il_b^b \le s_b^{j} \le H^m \ il_b^b \quad \forall b, j, t \tag{6}$$

Equation (7) denotes the production rate w_j^{o-j} of biofuel through the consumption of biomass b in the production process using technology q at plant j. The conversion rate of biomass to biofuel is given by the parameter μ_b^p . The mass balance of biofuel produced is also described by Equation (8) which states that the sum of biofuel produced w_j^{o-j} and stored inventory of biofuel $s_{j\ -1}^{j}$ at the plant in the previous period, t must equal the sum of biofuel delivered to distribution centers q_{jk}^{j} , and stored inventory of biofuel s_j^{j} in the current period t. Equation (9) defines the minimum inventory level il_j^E for biofuel at plant site j while equation (10) sets the upper and lower bound for the actual inventory stored at the site.

$$w_j^{o-j} = \sum_b (\mu_b^p \ w_b^{i-b}) \quad \forall j, p, q, t \tag{7}$$

$$\sum_q w_j^{o-j} + s_{j\ -1}^{j} = \sum_{k,m} q_{jk}^{j} + s_j^{j} \quad \forall p, j, t \tag{8}$$

$$il_j^E = \frac{\sum_{k,m} q_{jk}^{j}}{T_j^j} \ \forall j, p, t \tag{9}$$

$$H^m \ . il_j^E \le s_j^{j} \le H^m \ . il_j^E \quad \forall j, p, \mathrm{t} \tag{10}$$

Equation (11) is novel contribution that ensures the total new plant capacity b_j that can be used in production is applied at each plant sites j using technology q for each time t. boundary conditions for biofuel production rate is set by the equation

(12) with upper and lower bounds to total production capacity for each plants j, technologies q and periods. The parameter $\theta_{j,}^{j}$ is used to determine the lower bound for the production rate while τ_q also dictates the seasonal operation of plants. Production rate is a sum of existing capacity $E_{j,}^{j}$ and new capacities added $b_{j,}$. Equation (12) is modified from the original model to capture seasonal operation of biofuel plants.

$$b_{j} = b_{j,-1} + \sum_{s}\left(n_{j}^{j} + P_{j,}^{e}\right) \quad \forall j,q,t \tag{11}$$

$$\theta_{j,}^{j}\left(E_{j,}^{j} + b_{j}\right)\tau_q \leq w_{j,}^{o-j} \leq \left(E_{j,}^{j} + b_{j,}\right)\tau_q \quad \forall j,p,q,t \tag{12}$$

The new plant capacities $n_{j,}^{j}$ added to existing capacities for each plants j, technology q and plant size s is selected from discrete capacity levels s and technology q given by P_{q}^{j}. y_{j}^{j} is the decision variable that determines whether new plant capacity establishment takes place or not (i.e it can take the value1 or 0 respectively).

$$n_{j,}^{j} \leq P_{q}^{j}\, y_{j,}^{j} \quad \forall j,q,s,t \tag{13}$$

Equation (14) is a novel contribution which determines the capacity expansion allocated to an established new plant for each sites j, technology q, size s and period t.

$$p_{j}^{e} = \sum_{e} P_{q}^{j,}\, y_{j}^{j,} \quad \forall j,q,s,t \tag{14}$$

Equations (15)-(17) are novel contributions that establishes logical constraints for the model. Equation (15) states that the expansion decision $y_{j,}^{j,}$ is only feasible after the decision to establish the plant has been made while the decision to close a plant $y_{jq}^{j,}$, is also made after plant expansion. Equation (16) permits at most one capacity expansion in the plants while equation (17) ensures once a plant is closed $y_{j,}^{j,}$, its associated expansion capacity is also closed $y_{j,}^{j}$.

$$\sum_{e} y_{j,}^{j,} \leq \sum_{t' \in T: t' < T} y_{j,}^{j}, - \sum_{t' \in T: t' > T} y_{j,}^{j,}, \quad \forall j,q,s,t \tag{15}$$

$$\sum_{e} y_{j}^{j} \leq 1 \qquad \forall j, q, s \tag{16}$$

$$y_{j}^{j}, = \sum_{e} y_{j}^{j} \qquad \forall j \tag{17}$$

2.4 Petroleum fuel supply

Petroleum supply q_{rk}^{r} from existing petroleum refineries *r* to the blending centers *k* using transportation mode *m* at period *t* is bounded by the existing refinery capacity E_{r}^{r} for all periods and refineries in equation (18) while equation (19) defines the auxiliary variable f_{r} which describes the flowrates of petroleum product from refinery *r* in period *t*.

$$\sum_{k} q_{rk}^{r} \leq E_{r}^{r} \ \forall r, t \tag{18}$$

$$\sum_{k} q_{rk}^{r} = f_{r} \quad \forall r, t \tag{19}$$

2.5 Blending and Distribution centers

The equations in the Distribution center (DC) are similar to the ones for the biofuel plant stage of the supply chain. The mass balances of material inflows, inventory and consumption are accounted for by equations (20)-(22). Equation (20) states that the sum of biofuel delivered q_{jk}^{j} to Distribution Center *k* and stored inventory from the previous period $s_{k\ -1}^{k}$ must equal the sum of biofuel consumed in the blending process w_{k}^{i-k} and the inventory s_{k}^{k} in the current period. Equation (21) defines the inventory level il_{k}^{D} of biofuel which is the ratio of biofuel consumed to the turnover ratio T_{k}^{k} while Equation (22), provides upper and lower bounds for the biofuel inventory levels at the site *k* based on the factors H^{m} and H^{m}.

$$\sum_{j,m} q_{jk}^{j} + s_{k\ -1}^{k} = w_{k}^{i-k} + s_{k}^{k} \quad \forall k, p = b \qquad , t \tag{20}$$

$$il_{k}^{D} = \frac{w_{k}^{o-k}}{T_{k}^{k}} \ \forall k, t \tag{21}$$

$$H^{m} \ . il_{k}^{D} \leq s_{k}^{k} \leq H^{m} \ . il_{k}^{D} \quad \forall k, p = B \qquad , t \tag{22}$$

The mass balance of petroleum supply to DC is given by Equation (23) which states that the sum of fossil fuel delivered q_{rk}^{r} to Distribution Center *k* and stored inventory from the previous period s_{k-1}^{k} must equal the sum of fuel consumed in the blending process w_{k}^{i-k} at and the inventory s_{k}^{k} in the current period. Equation (24) defines the inventory level il_k^D of biofuel which is the ratio of fuel consumed to the turnover ratio T_{k}^{k} while Equation (25), provides upper and lower bounds for the fuel inventory levels at the site *k* based on the factors H^m and H^m .

$$\sum_{r,m} q_{rk}^{r} + s_{k-1}^{k} = w_{k}^{i-k} + s_{k}^{k} \quad \forall k, f = F \quad f \quad , t \tag{23}$$

$$il_k^D = \frac{w_{k}^{i-k}}{T_{k}^{k}} \qquad \forall k, t \tag{24}$$

$$H^m \ . il_k^D \le s_{k}^{k} \le H^m \ . il_k^D \qquad \forall k, f = f \quad , t \tag{25}$$

The mass balance of produced fuel blend from the distribution w_k^{o-k} is described by Equation (26) while equation (27) describes the ratios of biofuel to the overall blend rate O_{t} for the production of blends according to mandates. This representation does not consider the non-linearity associated with equations describing fuel quality and intermediate blends but presents the blend ratios of biofuel to petroleum fuel.

$$w_k^{o-k} = w_{k}^{i-k} + w_{k}^{i-k} \quad \forall k, t \tag{26}$$

$$w_{kt}^{o-k}{}_{k} = \frac{w_{k}^{i-k}{}_{k}}{O_{t}} \qquad \forall k, t \tag{27}$$

The new DC capacities n_{k}^{k} added to existing capacities for each Distribution Centers *k* and size *s* is selected from discrete capacity levels *s* given by $P_{k}^{k} . y_k^k$ is the decision variable that determines whether new blending capacity establishment takes place or not (i.e. it can take the value 1 or 0 respectively). Equation (29) on the other hand determines the capacity expansion allocated to an established new distribution/blending facility for each sites *k*, size *s* and period *t*.

$$n_{k}^{k} \le P_{k}^{k} . y_k^k \qquad \forall k, s, t \tag{28}$$

$$p_{k}^{k} \le P_{s}^{k} . y_k^k \qquad \forall k, s, e, t \tag{29}$$

Equation (30) is a novel contribution that ensures the total new plant capacity $d \quad_{k}$ that can be used in production is applied at each Distribution Centers *k* using for each periods *t*. Blend production rate limit is set by equation (31) with upper and lower bounds to total production capacity for each blending stations *k* and periods *t*. The parameter θ_k^k is used to determine the lower bound for the production rate. Production rate is a sum of existing capacity $E \quad_k^k$ and new capacities added $d \quad_k$.

$$d \quad_{k} = d \quad_{k \; -1} + n \quad_k^k + \sum_e p \;_k^k \qquad \forall k, s, t \tag{30}$$

$$\theta_k^k \left(E \quad_k^k + \sum_s d \quad_k \right) \leq w_k^{o-k} \leq E \quad_k^k + \sum_s d \quad_k \qquad \forall k, t \tag{31}$$

Equations (32)-(34) are novel contributions that establishes logical constraints for the model. Equation (32) states that the capacity expansion decision y_k^k is only feasible after the decision to establish plant has been made while the decision to close a plant y_k^k , is also made after plant expansion. Equation (33) permits only one capacity expansion in the plants while equation (34) ensures once a plant is closed y_k^k ,, its associated expansion capacity is also closed y_k^k .

$$\sum_e y_k^k \quad \leq \sum_{t' \in T : t' < T} y_k^k \;, - \sum_{t' \in T : t' > T} y_k^k \;, \quad \forall k, s, \tag{32}$$

$$\sum_e y_k^k \quad \leq 1 \qquad \forall k, s \tag{33}$$

$$y_k^k \;, = \sum_e y_k^k \qquad \forall k \tag{34}$$

Equation (35) describes the mass balance for the produced blends and flowrate of blend products delivered to demand zones from Distribution Center *k*. It states that the blends produced at *k* in period *t* should always equal the amount delivered to demand zones.

$$w_k^{o-k} = \sum_{d,m} q \;_{dl}^{k} \qquad \forall k, t \tag{35}$$

2.6 Demand Centers

At the demand center, the mass balance of blend products received and sales is given by equation (36) while equation (37) provides mass for the product sales and demand while taking into consideration unmet demand u_{d} .

$$\sum_{k,m} q_{d}^{k} = S_{d} \quad \forall d, t \tag{36}$$

$$S_{d} + u_{d} = D_{d} \quad \forall d, t \tag{37}$$

2.7 Costs constraints

The total capital investment ti_t^{in} is given as a sum of investment cost in biorefineries ti_j^{B} and distribution centers ti_k^{d} in equation (38) and is bounded by planned investment budget B in equation (39).

$$ti_t^{in} = \sum_j ti_j^{B} + \sum_k ti_k^{d} \quad \forall t \tag{38}$$

$$\sum_t ti_t^{in} \leq B \tag{39}$$

Fixed costs of the entire supply chain, for capacity opening, expansion, c0ontraction and closing in biorefinery and distribution center are defined by equations (40)-(42) respectively. Investment cost in biorefineries facilities ti_j^{B} and blending stations ti_k^{D} are defined by equations (40)-(41) whereas equation (42) describes the total facility closing cost ti_t. Equation (40) states that the total investment cost in biorefineries *j* for each periods *t* is the sum of the fixed capital investments F_q^{j} in opening new plants and fixed capital investment in the capacity expansion (contraction) F_q^{j} .

Equation (41) states that the total investment cost in Distribution center *k* for each periods *t* is the sum of the fixed capital investments F_k^{k} in opening new blending stations and fixed capital investment in the capacity expansion (contraction) F_k^{k} . Equation (42) states that the total facility closing cost ti_t, is the sum of the cost of closing a capacity and its associated expanded (contracted) capacity for biorefineries and distribution centers.

$$t\iota_j^B = \sum_{q,s}\left(F \quad {}_q^j \, y_j^j \quad + \sum_e F \quad {}_q^j \quad y_{j}^j \quad \right) \quad \forall j,t \tag{40}$$

$$t\iota_k^D = \sum_s\left(F \quad {}_k^k \, y_k^k \quad + \sum_e F \quad {}_k^k \quad y_k^k \quad \right) \quad \forall k,t \tag{41}$$

$$\begin{aligned} t\iota_t = & \sum_{j}\left(F \quad {}_q \, y_{j}^j \quad , + \sum_e F \quad {}_q \quad y_{j}^j \quad ,\right) \\ & + \sum_k\left(F \quad {}_k \, y_k^k \quad , + \sum_e F \quad {}_k \quad y_k^k \quad ,\right) \quad \forall t \end{aligned} \tag{42}$$

The processing cost c_t^p for all stages of the supply chain is given by equation (43). It is the sum of products of unit biomass processing $U \quad {}_b^i$ and harvested biomass bhs_b, unit processing cost for biomass $U \quad {}_b^j$ and biomass consumption rate w_b^{o-j}, unit blend production cost $U \quad {}_k^k$ and blend production rate w_k^{o-k}

$$\begin{aligned} c_t^p = & \sum_{b,i}(U \quad {}_b^H \, bhs_b \quad) + \sum_{j,b,q}\left(U \quad {}_b^B \, w_b^{o-j}\right) + \sum_k\left(U \quad {}_k^k \, w_k^{o-k}\right) \\ & + \sum_r(U \quad {}_r^r f \quad {}_r \,) \quad \forall t \end{aligned} \tag{43}$$

Transportation cost c_t^T of products and feedstock over all possible connections using all possible transportation modes in all periods are also accounted for in the equation (44). It states that for each period *t*, the total cost c_t^T is the sum of product of the unit transport cost for biomass *b* $U \quad C_b^B$, distance from harvesting site *i* to plant site *j* D_{ij}^{i} and flowrate of biomass $q \quad {}_b^i$ added to the product of unit transport cost for biofuel *b* $U \quad C_p^p$, distance from plant site *j* to distribution center *k* D_{jk}^{j} and flowrate of biofuel $q \quad {}_{jk}^{j}$, the product of the unit blend transport cost $U \quad C_p^p$, distance from distribution center *k* to demand center d D_{dl}^d and flowrate of finished blend $q \quad {}_{dl}^k$ and the product of the unit transport cost for fossil fuel *f* $U \quad {}_f^f$, distance from refinery *r* to distribution center *k* D_{rk}^r and flowrate of fossil fuel $q \quad {}_{rk}^r$.

$$
\begin{aligned}
c_t^T = \sum_m \Bigg(& \sum_{b,i,j} U \; C_b^B \; D_{ij}^{i} \; q_{b}^{i} + \sum_{p,j,k} U \; C_p^p \; D_{jk}^{j} \; q_{jk}^{j} \\
& + \sum_{p,j,l} U \; C_p^p \; D_{dl}^{d} \; q_{dl}^{k} \\
& + \sum_{f,k,r} (U_f^f \; D_{rk}^{r} \; q_{rk}^{r}) \Bigg) \; \forall t
\end{aligned} \tag{44}
$$

Storage costs for the products and feedstock for the integrated supply chain are accounted for by equation (45). It states that total storage cost c_t^S is the sum of the products of unit biomass storage cost U_b^B and inventory quantity s_{bj}^{j}, unit biofuel storage cost U_p^P and biofuel inventory at plant s_j^j, unit biofuel storage cost at distribution center U_p^P and the biofuel inventory at distribution center s_k^k and unit fossil fuel storage cost at distribution center U_f^f and the inventory of fossil at the distribution center s_k^k.

$$
\begin{aligned}
c_t^S = & \sum_{b,j} (U_b^B \; s_b^j) + \sum_{p,j} (U_p^P \; s_j^j) + \sum_{p,k} (U_p^P \; s_k^k) \\
& + \sum_{f,k} (U_{ft}^f \; s_k^k) \; \forall t
\end{aligned} \tag{45}
$$

The cost of unmet demand u_t is given by equation (46) which is a product of the cost of unmet demand u and quantity of unmet demand in demand zone d in period t u_d.

$$
u_t = U \sum_d u_d \quad \forall t \tag{46}
$$

2.8 Non-Negativity constraints

Equations (47)-(55) are non-negative constraints that ensure flow rates are either positive or zero.

$$
q_{jk}^{j} \geq 0 \tag{47}
$$

$$
q_{rk}^{r} \geq 0 \tag{48}
$$

$$q^{k}_{dl} \geq 0 \tag{49}$$

$$q^{i}_{b} \geq 0 \tag{50}$$

$$u_{d} \geq 0 \tag{51}$$

$$s^{j}_{b} \geq 0 \tag{52}$$

$$s^{j}_{j} \geq 0 \tag{53}$$

$$s^{k}_{k} \geq 0 \tag{54}$$

$$s^{k}_{k} \geq 0 \tag{55}$$

2.9 Objective Function

The objective function for this work is to maximize the Net present value (NPV) of the entire supply chain (equation (56)) which sums up the discounted cash-flows c_t obtained in each period *t* at the interest rate I . This accounts for the time value of the money and provides a comprehensive basis for profitability analysis (HUGO; PISTIKOPOULOS, 2005) of the supply chain.

$$M \qquad N = \sum_{t-1}^{t} \frac{c_t}{(1+I)^t} \tag{56}$$

The cash flow c_t is calculated by applying equation (57)-(58). Equation (57) states that the cash flow is the difference between the net earnings n_t and the fraction of total depreciable capital f_t for each period *t* except the last period, while in the last period *t=T*, salvage value S is recovered and added to the cash flow as described by equation (58). The salvage value S is assumed to be a factor of the total investment cost of the supply chain.

$$c_t = n - f_t \quad \forall t < C \quad (t) \tag{57}$$

$$c_t = n - f_t + S\ t^{i}_{t} \quad t = C \quad (t) \tag{58}$$

The net earnings n_t is calculated as the difference between the revenue from blend sales R_t and processing cost c^{p}_{t} , transportation cost c^{t}_{t} , storage cost c^{s}_{t} and the penalty for unmet demand u_t less the tax at the tax rate θ (equation (59)). Revenue r_t is calculated as the product of the price of blend in the domestic market L_k and product delivered to the distribution center q^{k}_{dl} plus revenue from sales of carbon credits earned by fuel distributors. Carbon credits will be elucidated upon further in the next section.

$$n\ _t = (1-\ \theta)\big[r\ \ \ _t - c_t^p\ - c_t^{t}\ - c_t^s\ - t\ \ _t - u\ \ \ _t\big] + \emptyset d\ \ \ _t\ \forall t \tag{59}$$

$$r\ \ \ _t = \sum_{k} L\ \ \ _k\ q\ {}_{d}^{k}\ \ + c\ \ _t P\ \ \ \ \forall t \tag{60}$$

It is assumed that the depreciation is linear over the period (Equation (61)). Hence, the fractional depreciable capital $f\ \ \ _t$ is calculated by dividing the total investment cost t_t^{i} the number of periods N (equation (62)).

$$d\ \ \ _t = \frac{(1-S\ \ )t_t^{i}}{N}\ \forall t \tag{61}$$

$$f\ \ \ _t = \frac{\sum_t t_t^{i}}{N}\ \ \forall t \tag{62}$$

2.10 Environmental assessment and objective

The environmental objective is to determine the global warming potential (GWP) $t\ \ _t$ of the supply chain constrained to meet annual nationally determined emission reduction targets $N\ \ \ \ \ \ _t$ for all period t is given by equation (63). The GWP is the sum of emissions from transportation t_t^{t}, processing t_t^{p} and fuel consumption $t\ \ _t$ activities across the entire supply chain for all period t (equation (64)).

$$t\ \ _t \le N\ \ \ \ \ \ _t\ \forall t \tag{63}$$

$$t\ \ _t = \ t_t^{t} + t_t^{p}\ _t + t\ \ \ _t\ \ \forall t \tag{64}$$

The emission from the transportation of feedstock and products is given as the product of emission factors E_m of associated transportation modes m, the relative distances between the source and destination and the mass of product transported. Equation (65) gives the sum of emissions from transport across all stages of the supply chain. The first term represents the transportation of feedstock to the biofuel plant, the second term represents the transportation of biofuel to the distribution centers from the plants, the third term represents emissions from transport of final blends to the demand centers from the distribution center and the fourth term represents the emissions from the transportation of fossil fuel from refineries or import to the distribution centers.

$$t\iota_{t}^{t} = \sum_{m} \left(\sum_{b,i,j} E\ {}_{m}D_{ij}^{i}\ \ q\ {}_{b}^{i} \ + \sum_{p,j,k} E\ {}_{m}D_{jk}^{j}\ \ q\ {}_{jk}^{jk} \right.$$

$$\left. + \sum_{d,k} E\ {}_{m}D_{dl}^{d}\ \ q\ {}_{dl}^{k}\ + \sum_{f,k,r} E\ {}_{m}D_{rk}^{r}\ \ q\ {}_{rk}^{r}\ \ ) \right) \forall t \tag{65}$$

Equation (66) gives the emissions $t\iota_{b}^{b}$ associated with the feedstock farming stage of the supply chain which is a product of the emission factors associated with the cultivation of biomass E_{b}^{H} and the harvested quantity bhs_{b}. The emissions associated with the production of biofuel at the plant $t\iota_{q}^{b}$, are given by equation (67), which is a product of emissions associated with using the biomass *b* for biofuel production E_{b}^{q} and the consumption rate of biomass w_{b}^{o-j} less of the emissions credit associated with the coproducts of each feedstock type.

$$t\iota_{bt}^{b} = \sum_{i} (E_{b}^{H}\ \mathrm{bhs}_{b}\ ) \quad \forall \mathrm{b,t} \tag{66}$$

$$t\iota_{qt}^{b} = \sum_{b,j} \left(E_{b}^{q} w_{b}^{o-j} - E\qquad {}_{b}^{q} w_{b}^{o-j}\right) \quad \forall \mathrm{q,t} \tag{67}$$

Emissions associated with the blending and distribution of blends and refining of petroleum fuel $t\iota_{t}^{d}$ are given as the product of the associated emission factor E^{k} and E^{r} and the blend production rate w_{k}^{o-k} and refinery production rate $f_{r,t}$ respectively (equation (68)).

$$t\iota_{t}^{d} = \sum_{k} \left(E^{k} w_{k}^{o-k}\right) + \sum_{r} \left(E^{r} f_{r,t}\right) \ \forall t \tag{68}$$

Equation (69) gives the total emissions attributed to the distributors of fuel, which is a sum of emission associated with the biomass cultivation $t\iota_{b}^{b}$, biorefinery processing $t\iota_{q}^{b}$ and distribution center processing $t\iota_{t}^{d}$. Whereas, emission associated with the consumption of fuels are given as a product of the emission factors for combustion of petroleum fuel E^{f} and biofuel E^{p} and the consumption rate of petroleum fuel w_{k}^{i-k} and biofuel w_{k}^{i-k} (equation (70)).

$$t\iota_{t}^{p} = \sum_{b} t\iota_{bt}^{b} + \sum_{q} t\iota_{q}^{b} + t\iota_{t}^{d} \quad \forall t \tag{69}$$

$$te_t = \sum_k (E^f w_k^{i-k} + E^p w_k^{i-k}) \; \forall t \tag{70}$$

A simplified case of carbon credits due to distributors in the *Renovabio* program is given by equation (71). This refers to Carbon emissions credits ci_t associated with production and processing of blends. It is given as a difference between the target set for the distributors of fuels T_t and the actual process emission te_t^p . This simplification does not take into consideration the non-linearity associated with the *Renovabio* model but only attempts to measure the level of compliance of distributors to set targets and the impact on profitability.

$$ci_t = T_t - te_t^p \;\; \forall t \tag{71}$$

3 Data Collection and Parameter Definitions

This section serves to provide information on parameters implemented in the model based on data from works of literature, databases and assumptions made in the case study. This will provide agricultural production data, biorefinery data and distribution data implemented in the model.

3.1 Agricultural production data

Supply of feedstock is assumed to come solely from farms owned by the plants, although it can come from other sources such as import or independent feedstock growers. Agricultural data considered include the feedstock type/selection, seasonality, productivity, cost and feedstock availability, which is based on several factors but for this work available land, biomass yield and seasonality and costs are the only factors considered. The following sections discuss these in details.

3.1.1 Feedstock selection

Production of ethanol in Brazil has been from sugarcane from the onset of the Pro-*alcool* era in the 1970s. Although largely simple in production technology and cheap, it has some drawbacks in that it can only be harvested for a maximum of seven months in a year and is highly perishable, hence plants are usually idle for 5-6 months resulting in job losses for a few months in the year and low plant capacity utilization. Consequently, there is a need to explore other feedstock options to improve capacity utilization of plants and boost production to meet growing demand (Antonio et al., 2010; Iglesias; Sesmero, 2015; Eckert et al., 2018).

Corn, as recommended by Antonio et al., (2010); and Eckert et al., (2018), has the potential to overcome the inherent limitations in the sugarcane ethanol supply chain. It brings the advantage of storability for up to 6 months in a year, high ethanol yield per tonne of feedstock, on and off-season production, and mature production and postharvest technology. The lower land costs, good sugarcane growing environment, and low-cost maize availability create the opportunity to increase ethanol production based on both raw materials.

3.1.2 Feedstock production and Seasonality

The yield of the selected feedstock varies in different product sites which are based on several factors such as soil fertility, climatic conditions, topography, farming practices, pest control etc. Table 1 presents the average yield of feedstock according to their harvest seasons in selected harvesting sites in Brazil. These seasons may vary slightly depending on region, climate, annual weather, and farming practices (PACK, 2007).

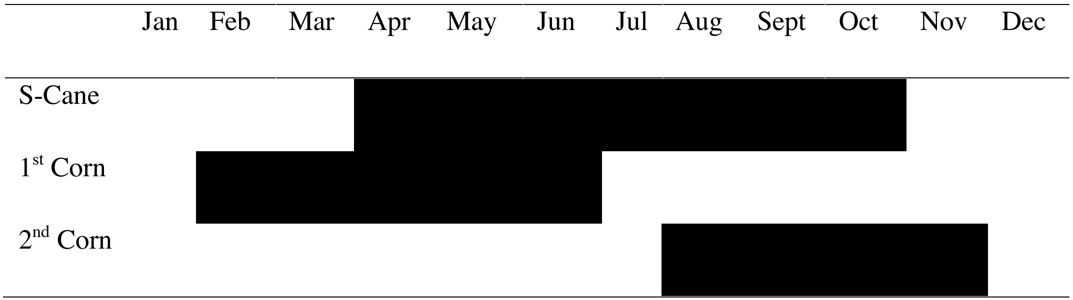
Table 1 Feedstock productivity (t/hectare/yr)

Location	index	Sugarcane	Corn (1st Harvest)	Corn (2nd Harvest)
			($t\ ha^{-1}\ yr^{-1}$)	
Acre	i1	26.3	2.3	0.0
Alagoas	i2	49.8	0.00	0.00
Amapá	i3	0.0	1.7	0.0
Amazonas	i4	67.5	2.5	0.0
Bahia	i5	30.8	4.21	3.18
Ceará	i6	4.9	1.06	0.00
Distrito Federal	i7	0	9.5	8.7
Goiás	i8	73.3	8.1	5.7
Maranhão	i9	40.5	2.37	3.72
Mato Grosso	i10	58.5	7.0	6.3
Mato Grosso do Sul	i11	76.0	8.9	4.9
Pará	i12	57.0	3.1	0.0
Paraíba	i13	49.9	0.66	0.00
Pernambuco	i14	45.8	0.83	0.00
Piauí	i15	49.7	2.57	3.71
Rio Grande do Norte	i16	31.5	0.61	0.00
Rondônia	i17	36.1	2.3	3.9
Roraima	i18	0.0	1.7	0.0
Sergipe	i19	37.2	0.00	0.00
Tocantins	i20	56.0	4.4	4.4

Source: (Embrapa, 2015; Unica, 2019)

Seasonality of feedstock production is a major drawback of biofuel production systems but measures such as the use of multiple feedstock and inventory management of feedstock can help overcome this limitation. As presented in Table 2, the harvest of sugarcane begins in April and ends in November but because of the perishability of sugarcane, it is only harvested and transported for the plant for immediate processing. Corn, on the other hand, is harvested earlier in the calendar year and also during the sugarcane harvest period, implying that during the sugarcane harvest period, corn can be stored for the sugarcane offseason period.

Table 2: Feedstock agricultural calendar



Source: (Antonio et al., 2010; USDA, 2016)

Although the production calendar is as shown in Table 2, the production and feedstock availability pattern assumed in this case study is shown in Table 3. The pattern was determined by prorating the number of months in a quarter when harvest is possible to the number of months harvest is possible in the year to determine the percentage harvest per quarter.

Table 3: Feedstock seasonal harvest pattern

	Quarter 1	**Quarter 2**	**Quarter 3**	**Quarter 4**
Sugarcane	0	0.43	0.43	0.14
Corn (1st & 2nd)	0.22	0.33	0.22	0.22

3.1.3 Agricultural Land availability

Feedstock production is dependent on the availability of land which is usually determined based on regional land use assessment and a survey of individual farm production. This parameter is also difficult to project beyond a few years owing to several types of risks and incentives that could cause changes in agricultural operations. Examples of such factors include Low-yielding seasons, market prices, land capital and operational costs. These may cause a farmer to expand or seek out alternative uses for the lands (PACK, 2007). The available cultivable land applied in this case study is given in Table 4.

Table 4: Available cultivable agricultural lands (thousand hectares)

Location	Index	Sugarcane	Corn (1st)	Corn (2nd)
			Planted Area (x 1000 ha)	
Acre	i1	3,059	41,500	0
Alagoas	i2	373,341	-	0
Amapá	i3	118	2,000	0
Amazonas	i4	4,120	11,250	0
Bahia	i5	107,490	458,250	230.5
Ceará	i6	24,763	494,500	0
Distrito Federal	i7	461	27,500	38.5
Goiás	i8	878,734	234,500	1181.25
Maranhão	i9	47,494	381,500	189
Mato Grosso	i10	277,294	59,000	4478
Mato Grosso do Sul	i11	617,923	20,250	1840
Pará	i12	13,295	66,750	0
Paraíba	i13	118,088	55,500	0
Pernambuco	i14	292,013	170,000	0
Piauí	i15	15,106	411,750	22.75
Rio Grande do Norte	i16	64,349	35,750	0
Rondônia	i17	4,126	35,750	129
Roraima	i18	366	6,250	0
Sergipe	i19	53,419	-	0
Tocantins	i20	33,754	61,000	139

Source: (EMBRAPA, 2015; UNICA, 2019)

3.1.4 Agricultural production costs

The agricultural production costs comprise of feedstock production cost, transportation costs, storage costs, and pre-processing costs. Feedstock production cost includes all cost involved in farming and harvest operations while storage cost is the cost of holding feedstock in storage. Transport of feedstock is majorly by trucking and associated costs are the cost of transport via trucks to plants and/or gathering centers. Preprocessing costs are costs of handling and transformation to forms and sizes that are adaptable to the Biorefinery plant. The costs considered in this case study are given in Table 5.

Table 5: Agricultural production costs

Item	Sugarcane	Corn	Unit
Production cost [a]	31.27	130.7	US$/t
Transportation cost [b]	0.32	0.03	US$/t-km
Storage cost [c]	No storage	14.07	US$/t

Sources:

a. Production costs of Sugarcane in northeast Brazil are R$96.01/t (PECEGE; CNA, 2016) converted at the exchange rate of R$3.07/USD$ while the production cost of corn is USD$4.74/Bushel (Meade et al., 2016) converted at 1 metric tonne and 25.4kg per bushel

b. Transportation costs of sugarcane and corn by truck were obtained from Khatiwada et al., (2016) and Sifreca, (2020), respectively.

c. Corn storage cost of R$43/t was obtained from Yabe Milanez et al., (2014) and converted at the exchange rate of R$3.07/USD$

3.2 Biorefinery Data

A biorefinery facility includes feedstock storage, processes for feedstock conversion to an end product, and end product inventories. Biorefinery data presented in the following sections include existing ethanol production capacity, biorefinery technologies, biorefinery capacity, material conversion factors or technology coefficients and their associated capital, costs of expansion and operating costs.

3.2.1 Existing production capacity

The current production of ethanol in Brazil is primarily from sugarcane using both first and second-generation production technologies although new plant designs of flex nature are being adopted as well. The total ethanol production capacity in the Northeastern states as extracted from (UNICA, 2019) is presented in Table 6:

Table 6: Average ethanol production capacity in the Northeast of Brazil (T ethanol /Year)

Location	Index	Production Capacity (T/yr)
Alagoas	J1	386,932.70
Bahia	J2	193,855.72
Ceará	J3	-
Maranhão	J4	116,705.72
Paraíba	J5	301,398.00
Pernambuco	J6	340,763.58
Piauí	J7	29,571.72
Rio Grande do Norte	J8	82,826.85
Sergipe	J9	79,611.68

Source: (UNICA, 2019)

3.2.2 Technology

There are three (3) production pathways considered in this case study which are all of the biochemical conversion route: Autonomous Sugarcane ethanol plants, Corn dry Mill and flex mill. The process for producing ethanol from sugar or starchy crops is almost identical from the fermentation process onwards. Both processes yield residues and by-products that typically have some value. For sugar cane, bagasse is left over that can be used to fire combined heat and power (CHP) plants to provide process heating and electricity needs for the biofuels plant and potential exports to the grid while with starchy crops, dried distiller grain can be produced and sold as feed to various livestock industries (International Renewable Energy Agency, 2013).

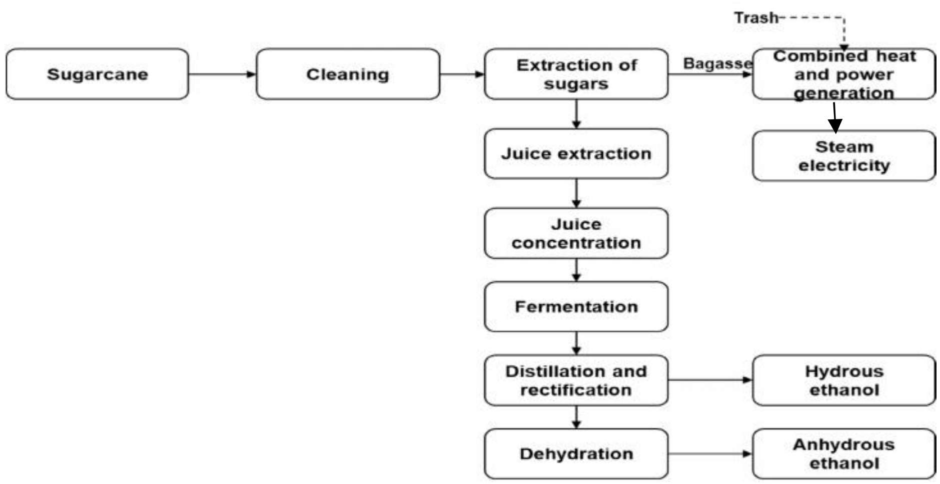
3.2.2.1 Autonomous Sugarcane biorefinery

In an autonomous distillery, all processed sugarcane is used for ethanol and electricity production (Junqueira et al., 2011). The production process as shown in Figure 3 involves the reception and cleaning of cane, after which, it is sent to the mills for juice extraction. Bagasse from the juice extraction stage is then sent to the boilers to be used as fuel in the cogeneration system to supply the plant’s energy and heat demands and surplus electricity for the grid.

The extracted Sugar juice undergoes treatment involving the removal of impurities and concentration, producing both clarified juice and filter cake. The clarified juice then goes to the fermentation tanks to be mixed with diluted yeast to produce a fermented solution containing ethanol and carbon dioxide (CO_2), which is vented into the atmosphere.

At the end of this stage, yeast recovery is carried out by centrifugation and reused and the Filter cake is sent to the fields to be used as fertilizer. The fermented solution is further distilled into ethanol, vinasse, and fusel oil. Vinasse is diluted and used for soil fertigation in the fields (Donke et al., 2016).

Figure 3: Sugarcane ethanol production pathway



Source: Author

3.2.2.2 Dry Mill Ethanol Pathway

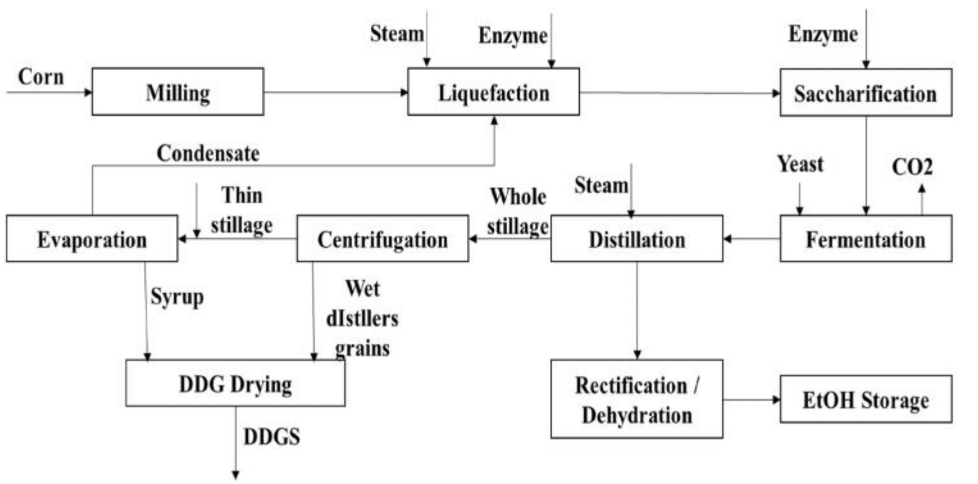
As already stated, the corn ethanol process is similar to the sugarcane ethanol process, and is only differentiated because of the extra equipment requirement involving the grain handling, and hammer mill (preprocessing) equipment as well as the starch digestion equipment (Iglesias; Sesmero, 2015b).

The production process involves the reception of the raw material (Corn), which is conveyed to storage silos. Stored corn is then sent for grain-cleaning where trash such as tramp metal and rocks are removed and then transported to the hammer mills to be crushed into a meal.

The meal is then metered to a continuous liquefaction tank, where it is mixed with hot evaporator condensate and purchased alpha-amylase enzyme. After liquefaction, backset (recycled thin stillage from the centrifuge) is added, amounting to 15% by volume of the final mash. Continuous saccharification takes place in a stirred tank with the addition of glucoamylase and sulfuric acid for pH control. The saccharified mash is cooled to 32°C (89°F) and fed to continuous cascade fermenters where yeast is added with a total residence time of 46 hours (Mcaloon et al., 2000).

Finally, separation of hydrous ethanol (95%w/w) from the vinasse is carried out by distillation. However, yeasts are unrecoverable in the dry milling process, hence, the vinasse and the soluble solids are recovered and used as a protein component in animal feed. Converse to the sugarcane ethanol production process, heat and energy are supplied by natural gas or other alternative fuels but with same cogeneration system (Donke et al., 2016).

Figure 4: Dry Mill Ethanol process



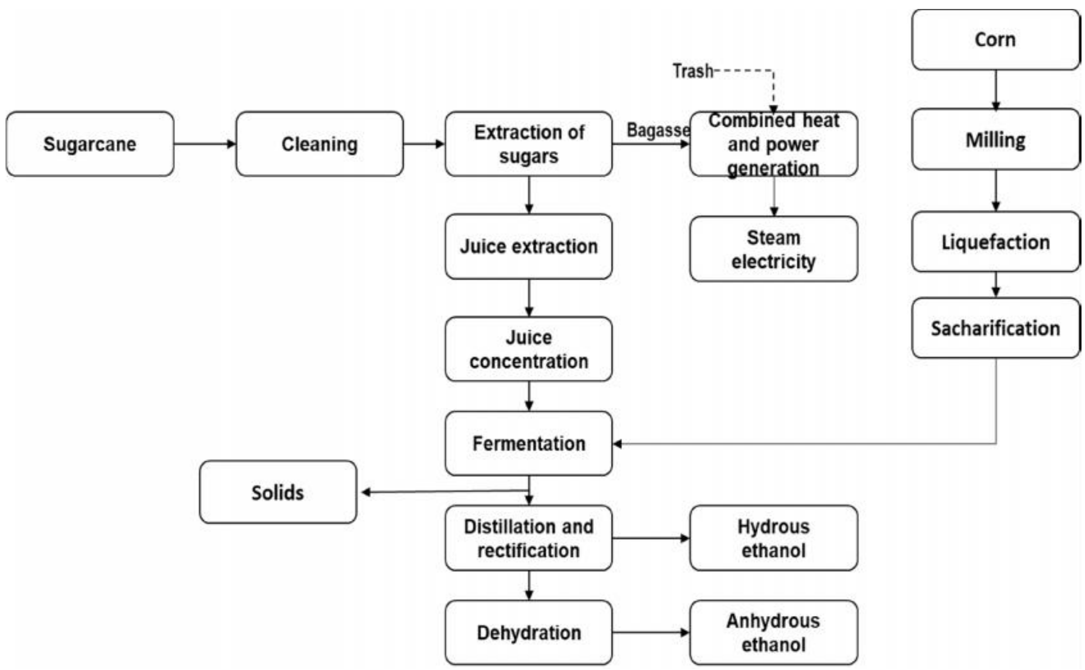
Source: (Tucker et al., 2004)

3.2.2.3 Flex Mill Biorefinery

Flex mills are ethanol production plants with the capacity to process both feedstocks (sugarcane and corn). As in the case of Brazil, the sugarcane ethanol plants are retrofitted to process corn and share already existing equipment, therefore, there is no additional plant built but equipment such as the grain handling, and hammer mill (preprocessing) equipment, as well as the starch digestion equipment, are added (Iglesias; Sesmero, 2015b).

This technology presents the advantage of the use of multiple feedstocks and overcomes the limitation of capacity utilization of sugarcane biorefineries caused by seasonality and perishability of sugarcane feedstock (Antonio et al., 2010; Iglesias; Sesmero, 2015b; Donke et al., 2016). The use of multiple feedstocks is one way to improve capital utilization efficiency as this helps to compensate for low energy density properties and poor capital utilization elsewhere in the system. The flex mill concept is hypothesized to allow sugarcane ethanol mills to compete more effectively with traditional and other alternative fuel models by allowing the use of a second feedstock; maize or sorghum (Antonio et al., 2010).

Figure 5: Flex mill production pathway



Source: Author

3.2.3 Conversion factors

Conversion factor is also known as a technology coefficient. Each factor is unique to each ethanol production pathway or feedstock. It is measured in units of mass or volume of product per unit of mass or volume of feedstock. Conversion factors may vary due to the equipment configuration and scale, process conditions, and control settings, feedstock origin (since the material quality is a function of farming practices), land quality, feedstock composition, seasonality, natural decay, and other time-dependent feedstock characteristics.

Finally, it also depends on the type of product to be produced based on their respective underlying chemical reactions as different products would have different conversion efficiencies from same feedstock (Pack, 2007). Table 7 gives the technology coefficients for converting corn and sugarcane into ethanol. A unique conversion efficiency is assumed for both hydrous and anhydrous ethanol.

Table 7: Feedstock conversion factors

Feedstock	**Conversion efficiency (Liters /t Feedstock)**	**Conversion efficiency (t Ethanol /t Feedstock)**
Corn	400	0.32
Sugarcane	90	0.063

Source: Conversion efficiencies in Liters/t feedstock obtained from (ECKERT et al., 2018) and converted to t ethanol/t Feedstock by multiply by ethanol density (789kg/m^3) and the ratio of liquid volume in cubic meter to litres (0.001m^3/L)

3.2.4 Biorefinery Costs

Biorefinery costs include capital costs of establishing new plants and operational costs of plants of ensuring proper operations of the facilities. These costs vary with plant capacity as a result of the economics of scale, feedstock and procurement logistics, production pathway etc. the details of biorefinery capital and operation costs are discussed in the following sections.

3.2.4.1 Capital cost

The costs for establishing new biorefinery capacities used in the case study are derived by using the total installed capital costs for the prototype plant technology as shown in Table 8 and adjusted using equation (72) to meet the capacity requirement for the cases study. The facility capacity is scaled from the prototype plant using equation (72) applying a 0.65 scaling factor.

$$\left(\frac{C \quad A}{C \quad B}\right) = \left(\frac{S \quad A}{S \quad B}\right)^{0.6} \qquad (72)$$

Where $C \quad A$ is the capital cost of the new plant capacity with a $S \quad A$ whereas $C \quad B$ is the cost of the known capacity of the prototype plant $S \quad B$.

Table 8: Base Capital costs of prototype plants

Biorefinery Technology	Processing capacity (Mt feedstock/Year)	Capital Cost (USD$)
Autonomous sugarcane[a]	2.5	191,445,370.00
Corn Dry mill [b]	0.95	211,247,000.00
Flex Mill [c]	Sugarcane: 2.5 Corn: 0.208	257,011,995.00

Source:

a. (IGLESIAS; SESMERO, 2015)

b. (JOHANNS, 2020)

c. (IGLESIAS; SESMERO, 2015)

Hence, the derived costs for predetermined discrete capacity for ethanol production are given in Table 9.

Table 9: New plant capacities and costs

Production pathway	50kt Ethanol/yr S1	100kt Ethanol /yr S2	150kt Ethanol /yr S3
Autonomous sugarcane (USD$)	89,509,918	135,671,665	173,038,966
Corn Dry mill	72,120,079	109,313,598	139,421,241
Flex Mill	97,150,730	147,252,971	187,810,047

Furthermore, expansion and contraction costs are assumed to be 50% of the cost of the new capacity to be attained while the closing cost is given as 10% of the capital cost of the existing plant capacity.

3.2.4.2 Operating Cost

The operating costs consist of the cost of producing a unit of ethanol for a production pathway, cost of inventory at the plant and transportation to the distribution centers. Processing cost represents all non-feedstock operating costs, including operation and maintenance of the conversion process, labour, utilities, engineering, general and administrative costs. The storage cost represents the port fees including storage cost as indicated (Crago et al., 2010) while transport cost represent the cost transport (USD$) of a tonne of ethanol per kilometer (km). Table 10 presents the cost used in this case study.

Table 10: Pathway operating cost

	Autonomous sugarcane biorefinery	Corn Dry mill biorefinery	Flex Mill biorefinery	unit
Processing cost[a]	177.4	240.8	S-cane: 177.4 Corn: 240.8	US$/t EtOH
Ethanol Storage cost[b]	13.1	13.1	13.1	US$/ t EtOH
Transport cost[c]	Truck: 0.034 Rail: 0.021	Truck: 0.034 Rail: 0.021	Truck: 0.034 Rail: 0.021	US$/ t EtOH -km

Source:

a. Ethanol processing cost for sugarcane and corn are given as USD$140 and USD$190 per cubic meter respectively and converted by multiplying ethanol density of 789 kg per cubic meter (Crago et al., 2010).

b. Ethanol storage costs at the ports are also assumed to be the cost of storage at the plant at R$27 per cubic meter and converted at an exchange rate of R$2.62 per USD$ as stipulated by Crago et al., (2010).

c. Transportation cost of ethanol by rail and truck is obtained from Scandiffio, (2010); Sifreca, (2020).

3.3 Blending and Distribution centers

Blending and distribution centers are responsible for supplying gasoline and ethanol, storage, blending anhydrous ethanol with gasoline, transportation and commercialization, and ensuring product quality control. The planning of distribution centers is also a strategic decision as it is from this point ethanol blends are transported to final consumers (Scandiffio, 2010). This section provides information on existing distribution capacities, capital and operating costs for new investments.

3.3.1 Existing blending capacity

Product distribution to demand centers takes place at the distribution and blending facilities. Here products are blended to meet the National Blending Mandates of the country, and quality assurance of products is also ensured to meet market standards. In

Brazil, the blends consumed are the Gasoline C which is a blend of 27% anhydrous ethanol and 73% pure gasoline, while hydrated ethanol which is denatured (fuel) ethanol is also consumed by flex-fuel cars.

Table 11 presents the current distribution capacity within the northeast region of the country for ethanol and petroleum derivatives (ANP, 2018). In this case study, the total distribution capacity for ethanol and petroleum products is applied for gasoline storage and blending.

Table 11: Distribution bases Nominal storage capacity (m^3/period)

Location	Index	Ethanol (m^3)	Petroleum Derivatives (except LPG) (m^3)
Alagoas	K1	3,875.00	32,934.00
Bahia	K2	31,352.71	139,697.94
Ceará	K3	16,696.25	97,245.95
Maranhão	K4	10,931.38	129,767.22
Paraíba	K5	6,900.49	27,038.79
Pernambuco	K6	15,809.55	88,102.56
Piauí	K7	2,497.69	13,652.35
Rio Grande do Norte	K8	20,586.48	54,381.04
Sergipe	K9	3,661.00	20,092.00
Northeast Region	**Total**	**112,310.55**	**602,911.85**

Source: (ANP, 2018)

3.3.2 Blending and distribution center costs

The blending and distribution costs comprise the capital costs of establishing distribution bases and the operational costs of production such as distribution cost, inventory holding cost and distributing final blends.

3.3.2.1 Capital Cost

The capital cost, as shown in Table 12, is the cost of building new bases or expanding existing capacity. The distribution base is composed of several components such as storage tanks, blenders network of pipeline, pumps, control valves, intake manifolds etc. the capacity sizes assumed in this case study are 300 kt/yr, 750 kt/yr and 1200 kt/yr of processing capacity in addition to the existing capacity and the cost of capacities were assumed to be USD$31.40/t, USD$ 22.78/t and USD$ 19.33/t of processing capacity (Equation 65).

Table 12: Distribution center Capital costs and associated capacity

	Capacity level (S)		
	300kt/yr	**750kt/yr**	**1200kt/yr**
Cost (USD$)	9,418,572	17,086,222	23,191,244

These costs are based on the estimates of 25 kbbls tank storage at USD$ 450,000 (@USD$18 per barrel) blending system cost of USD$ 300,000 per terminal, Rail-spur receipt installation at USD$ 355,000 per terminal and miscellaneous contingency cost at USD$20,000 per terminal, obtained from Reynolds, (2002). Tank storage capacity is converted at 0.125 t-Ethanol per barrel and added to the cost of blending systems, rail-spur installation and contingency cost per terminal.

3.3.2.2 Operational costs

Operational costs of distribution centers include blend production cost, fuel inventory cost, gasoline-A purchase cost from petroleum refineries and transportation costs. These costs are outlined in Table 13;

Table 13: Operational costs of the distribution center

Item	Cost (USD$/t)
Processing cost[a]	12% of product price
Inventory cost[b]	13.1
Transportation cost[c] per kM	Truck: 0.034
	Rail: 0.021
Gasoline A cost[d]	937.78

Source:

a. Assumption based on composition gasoline price published by Petrobras, (2020)

b. Fuel storage cost at DC is also assumed to be same as the cost of storage at the plant at R$27 per cubic meter and converted at an exchange rate of R$ 2.62 per USD$ as stipulated by CRAGO et al., (2010).

c. Transportation costs of ethanol by rail and truck are obtained from SCANDIFFIO, (2010); SIFRECA, (2020).

d. Gasoline cost is obtained from ANP, (2018) at R$ 2.142/Litre (2017) and converted by multiplying the reciprocal of gasoline density of 0.744-t Gasoline per cubic meter and dividing through by the exchange rate of R$ 3.07 per USD$

3.4 Petroleum supply

Petroleum supply is primarily from refineries and in case of a supply deficit, imports are made to equalize demand. The details of petroleum refining are complex and will not be considered in this work, however, for this case study, the existing petroleum refineries in the North and Northeastern regions of Brazil are used in the planning problem. Full capacity utilization is assumed for the plants while the mass of gasoline produced is assumed to be 28.7% of the total production capacity based on current product slate analysis (ANP, 2018). Table 14 gives a summary of the existing refining capacity within the region.

Table 14: Existing refining capacity in the North and Northeast regions

Refinery	Index	Location	Nominal capacity barrels/day	Nominal Capacity barrels/year	Nominal Capacity t/year
Rlam	R1	São Francisco do Conde (BA)	377,389	124,538,238	16,808,369
Repar	R2	Araucária (PR)	213,853	70,571,490	9,524,719
Reman	R3	Manaus (AM)	45,916	15,152,152	2,045,018
RPCC	R4	Guamaré (RN)	44,658	14,737,001	1,988,987
Dax Oil	R5	Camaçari (BA)	2,095	691,187	93,286
Total			**683,909**	**225,690,069**	**30,460,380**

Source: (ANP, 2018)

3.5 Product demands

Product demand is unique to each location based on their consumption patterns. The ethanol market demand is linked to gasoline consumption because of its substitutionary role in the petroleum sector either as hydrous ethanol or blends of gasoline and ethanol such as Gasoline-C (E27) in Brazil at terminals or distribution centers. Forecasting demand is generally carried by taking into consideration historical data, national fuel mandates and other factors such as a change of government and policies, however, consideration of mandates and historical trends can be used in demand forecasting to a reasonable level of accuracy (PACK, 2007).

For this case study, base annual fuel demand are presented in Table 15 and projected to grow at 6% and 10% growth rate per year for gasoline-C and hydrous ethanol respectively, whereas the national mandates remain unchanged for the period in consideration.

Although, demand data provided in Table 15 are annual values, they were further prorated to quarterly values according to the analyzed quarterly consumption trend i.e. Quarter 1: 25.23%, quarter 2 & 3: 24.06%, and quarter 4: 26.31% of total annual values. Quarterly growth rate were also estimated from data to be 1.62%, 1.62%, 1.63% and 1.65% quarter on quarter respectively over the planning period for the case study. Demand data applied in this case study are provided in Appendix A.

Table 15: Average Fuel demand in the Northeastern states (T/year)

Location	Hydrous Ethanol	Gasoline C
Alagoas	40061.3	341876.8
Bahia	314179.8	1662041.9
Ceará	120016.4	1055920.9
Maranhão	30343.2	724747.3
Paraíba	89465.3	528020.3
Pernambuco	207623.1	1096873.7
Piauí	36250.1	456570.3
Rio Grande do Norte	55034.0	500286.8
Sergipe	27914.8	304305.9

Source: ANP, (2019)

The product prices considered in this case study are shown in Table 16 below. Although these represent prices of individual products sold in the Brazilian market, and overall blend price that represents the aggregate price obtained from both products based on the ratio sales is obtained and used in this case study. The prices are escalated according to the escalation factor at 2% annually.

Table 16 Product sales prices by distribution centers

Product	Price[a] (R$/Litre)	Price[b] (USD$/t)
Gasoline C	**3.77**	**1627.01**
Hydrous Ethanol	**2.71**	**1120.66**
Overall Blend[c]		**1,574.02**

Source:

a. Gasoline C and hydrous ethanol price are obtained from ANP, (2018) and UNICA, (2019) at 2017 and 2018 value respectively. The hydrous ethanol price is the consumer price in São Paulo state and it is an average of the monthly prices in 2018.

b. Cost in USD$ per t are calculated by multiplying the reciprocal of gasoline C and hydrous ethanol densities of 0.75435-t Gasoline per cubic meter and 0.789 t hydrous and the prices obtained in (a) above then dividing through by the exchange rate of R$ 3.07 per USD$ respectively.

c. Overall blend price is calculated by multiplying the prices of an individual product by the percentage share of sales summing to obtain a single price. In this case, from analysis 10% of total sales for the case study is hydrous ethanol multiplies is the price of USD$ 1120.66 per t and added to gasoline C sales accounting 90% of sales multiplied by its price of USD$ 1627.01 per t to obtain USD$ 15720.02 per t

3.6 Environmental parameters

The environmental parameters considered in this case study are Greenhouse gas emission targets set for the region in consideration and the emission factors of the various processes involved the entire supply chain.

3.6.1 GHG emission and reduction target

Emission data were obtained from (SEEG, 2018) website, which are estimates that cover GHG emissions in Brazil, its states and federal district from 1970 to 2018 for all sectors-Agriculture, Energy, Land Use Change, Industrial Processes and Waste, except land-use change, covering the period from 1990 to 2018. These estimates are according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and data are obtained from government reports, institutes, research centers, sector entities and non-governmental organizations.

The gases covered in this report include Carbon dioxide (CO_2), methane (CH_4), Nitrous oxide (N_2O) and Hydrofluorocarbons (HFC) and are presented in carbon dioxide equivalent (CO_2e). Table 17 presents the carbon dioxide equivalent of the emissions from the energy sector in the northeast of Brazil considering fugitive and fuel combustion emission in from the transport sub-sector.

A total of 38 million tonnes of CO_2e was emitted in the year 2018 from this sub-sector, however, the government has a plan to reduce carbon emissions by 10% in ten years from 2018 levels while encouraging wider use of biofuels. This initiative is to be induced by the RenovaBio program that incentivizes efficiency in feedstock and fuel production processes (Global Carbon Atlas, 2018; SEEG, 2018).

Table 17: Total emissions from the energy sector in 2018

States	Emission (TCO_2e)
Alagoas	1,716,019.41
Bahia	11,448,639.16
Ceará	5,331,484.86
Maranhão	5,181,689.77
Paraíba	2,261,013.81
Pernambuco	5,927,332.64
Piauí	2,337,004.53
Rio grande do Norte	2,441,564.26
Sergipe	1,449,596.08
Grand Total	**38,094,344.51**

Source: SEEG, (2018)

3.6.2 Supply chain GHG emission factors

There are emissions from all activities along the supply chain i.e. feedstock production, industrial processes and transportation of feedstocks and finished products and several attempts have been made to estimate emissions from the production of corn and sugarcane ethanol.

For the sake of comparison, only emission factors from the same sources are used for corn ethanol and sugarcane ethanol. The emission factors for both corn and sugarcane for each stage of the process are shown Table 18.

Table 18: GHG emission factors

Ethanol production				
Item	**Sugarcane**	**Corn**	**Unit**	**Source**
Feedstock farming	24.29	213.22	kg/t feedstock	(GREET, 2019)
Ethanol production	412.34	998.28	kg/t EtOH	(GREET, 2019)
Emission credit	24.2	96.2	kg/t feedstock	(MACEDO; SEABRA; SILVA, 2008; CRAGO et al., 2010)
Refining emissions (Gasoline)		130	Kg CO2 per barrel of gasoline	(JEREMY MARTIN, 2017)
Blending & Distribution emissions		737	Kg CO2 per t blend	(GREET, 2019)
Transportation				
Rail		0.021	KG CO2e per t-km	(EPA, 2014)
Truck		0.125	KG CO2e per t-km	(EPA, 2014)
Combustion emission				
Ethanol		5.75	Kg CO2 per gallon	(EPA, 2014)
Gasoline		8.78	Kg CO2 per gallon	(EPA, 2014)

3.7 Spatial Modelling Considerations

Biorefinery sites, distribution centers and demand locations in the system are within the same region, however, harvesting sites have wider coverage and other regions are considered as potential feedstock sources. From a material flow perspective, this system can be considered closed since the feedstock supply chain and distribution network are entirely defined by the model and parameters. The model formulation permits great flexibility in the geographical interpretation of the actual system (PACK, 2007).

The guidelines considered for the spatial modelling frame considered include

1) Each location contains a single harvesting site.

2) Each harvesting site cannot exceed the available cultivable land limit.

3) The location of each harvesting site is assumed to be the geometric center of the state.

4) Each location can contain more than one biorefinery.

5) Biorefineries are located in the geometric center of their states.

6) Each demand center is a unique location.

7) Demand centers are located in the geometric center of their locations.

8) A single location may contain a biorefinery, harvesting site, distribution center and demand center.

9) The distances between them between harvesting site, distribution center and demand center within the same location are assumed to be zero

The relative distances between sites are given in Annex A.

3.8 Model Validation

The model was validated using trivial validation and case study methods. These are described in the following sections.

3.8.1 Trivial validation

The model was validated using the trivial validation methodology which is used to check the internal consistency of the model itself. Internal consistency refers to the logical accuracy of the equations and the code for computer implementation. This assumes that all conversion factors are equal to 1 throughout the entire supply chain and implies that one unit of feedstock produces one unit of product. Also assumed is that there is no decay of feedstock during storage. This removes the complexity of conversion factors to allow traceable flows of materials through the system (PACK, 2007).

3.8.2 Case study

A case study of the northeast of Brazil is carried out where there is a need for investment in ethanol biorefineries as a result of its production capacity deficit (ANP, 2017). Feedstock alternatives considered include corn and sugarcane for ethanol production. The biochemical conversion process is explored and proposed production pathways considered are corn Dry Mill ethanol, autonomous sugarcane ethanol and flex-mill (corn and sugarcane) technologies. Demand data used for this case study is obtained from historical data of the 9 demand locations and projected according to the historical average growth rate of fuel consumption. 20 potential harvesting sites, 9 potential ethanol plant and blending location alternatives and 5 potential petroleum refinery supply locations were considered in this case study to form the network. Quarterly time scales for a 10 year (40 periods) were also adopted so as to factor in seasonal patterns of feedstock production.

The case study also considered the implementation of environmental constraint according to the nationally determined targets to reduce CO_2 emissions by 10% in 10 years from the 2018 emissions record levels (SEEG, 2018). Furthermore, a simplified *Renovabio* carbon trading scheme case is considered to measure the possibility of compliance of distributors to emission reduction targets set for them which is patterned like the national periodic targets. Annual emissions were prorated equally over each quarterly period and quarterly reduction targets were set to 0.26% quarter over quarter both national and distributors emission targets.

4 Computational implementation, Results and Discussions

4.1 Optimization software package and model code

The optimization software used in this modelling effort is the Excel-GAMS interface, version 23.02. The GAMS software combines the language of mathematical algebra with traditional concepts of computer programming to efficiently describe and solve optimization problems. It is equipped with several solvers to solve linear and non-linear systems, however, the CPLEX 11.2.1 solver was used in this current study using branch and cut algorithms (GAMS, 2020).

The model was solved on an ASUS S56C series computer with 4GB RAM and Intel Core I5-3317U-1.7GHz in a windows 10 environment. It was applied to the case study over a 10-year time horizon consisting of four (4) quarters per year. It consisted of 35,711 single equations, 101,952 single variables and 35,790 discrete variables. The model was solved to optimality in 24:33:53.315 (HH:MM:SS) with an optimality gap of 0%.

4.2 Trivial validation

Appendix B presents the results of the trivial validation of the model where all conversion factors were set to 1 to check the model consistency. We observe the biomass harvest equals the total processed which in turn equals the total biofuel produced for each period. Hence, no difference between the feedstock and the product indicate model consistency. There is no feedstock inventory as sugarcane, the selected feedstock, cannot be stored as a result of the degradability.

4.3 Northeast Brazil Case study

Detailed validation results from the case study in the Northeast of Brazil can be found in Appendix C and further analyzed and discussed in the following sections. A top-down approach is adopted in discussing these results, moving from the high-level economic results to a detailed analysis of results from each stage of the supply chain, including harvesting sites, biorefineries, distribution centers petroleum supply, and demand satisfaction.

4.3.1 High-level Economic results

The model calculates several economic variables including the capital and operating costs, product sales revenue, carbon credits and the Net Present Value of the supply chain. A summary of the economics of the supply chain is shown in Table 19.

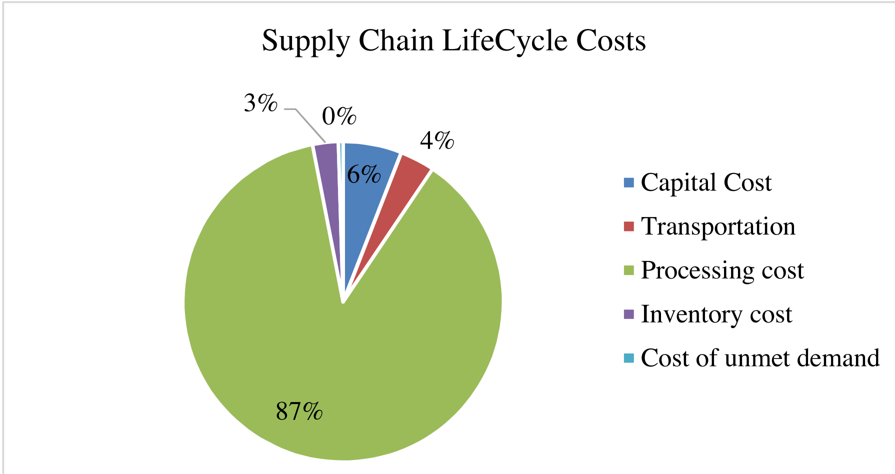
Table 19: High-Level Economic summary of the dynamic and traditional capacity strategy

Item	Dynamic Capacity Strategy	Traditional Capacity Strategy	Difference
	(USD$)	(USD$)	
NPV	**25,336,005,625**	**25,210,973,664**	**125,031,961**
Optimality gap	0.00%	0.00%	0.00%
Capital Cost	**3,078,383,538**	**3,000,398,148**	**77,985,389**
Biorefinery	3,051,878,743	2,973,893,353	77,985,389
Distribution Center	26,504,795	26,504,795	0.00
Variable Costs	**48,948,463,881**	**49,151,517,386**	**-203,053,505**
Transportation	1,834,987,620	2,015,489,022	-180,501,402
Processing cost	45,514,011,291	45,531,902,010	-17,890,719
Inventory cost	1,353,192,732	1,347,962,350	5,230,383
Cost of unmet demand	246,272,238	256,164,004	-9,891,766

Table 19 gives a snapshot of the economics of the lifecycle costs, and net present value of the supply chain. It shows that the dynamic capacity is more profitable over the period considered. The capital costs of the dynamic capacity strategy are higher because the cost of contraction of capacities while the variable cost of the traditional strategy is also higher as a result of more consumption of sugarcane according to the results. The higher consumption of more sugarcane, in the traditional strategy, implies higher transportation, and processing cost. However, because sugarcane cannot be stored, this trend does not impact on inventory. In fact inventory was less than that of dynamic capacity strategy that used more corn.

Figure 6 gives a breakdown of the lifecycle cost of the supply chain. As can be observed the processing cost across the supply chain is the greatest accounting for 87% of total cost while the total capital cost accounted for 6% and inventory and transportation cost accounted for 7%. Cost of unmet demand was significantly low due to high level of demand satisfaction

Figure 6: Supply chain lifecycle cost breakdown



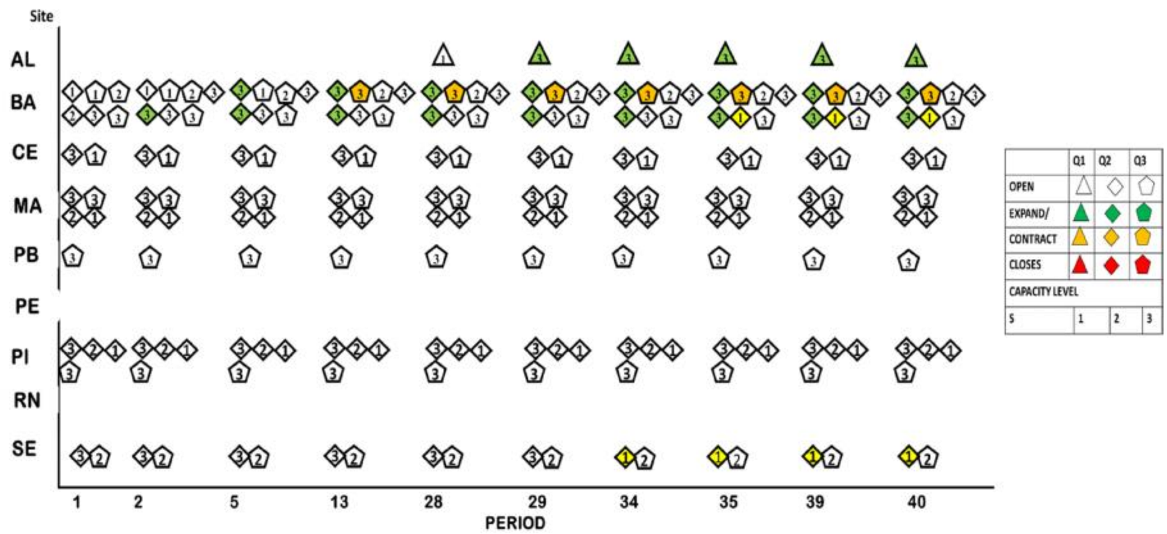
4.3.2 Facility location and Evolution of capacity

The capacity addition and evolution profile as given by Table 20 and graphically represented in Figure 7 show significant investments in technology with corn processing ability such as Q2 and Q3 technology (1350 & 900 kt/yr. respectively). Biorefinery capacity investment profile also shows that most plants were installed in the first and second periods owing to the immediate need to overcome the production deficit. Site J2 (Bahia) had the highest number of plants and also the largest total capacity installed in the period used in this work and the least investment in J1 (Alagoas) with only one plant installed of the Q1 (autonomous sugarcane pathway) having 50 kt/yr ethanol production capacity.

Table 20: Biorefinery capacity profile

CAPACITY INSTALLATION PROFILE					
Site	**Index**	**Period**	**Technology Capacity (Number of plants/Total capacity installed, Kt/yr.)**		
			Q1	**Q2**	**Q3**
Alagoas-AL	J1	28	1/50	-	-
Bahia -BA	J2	1	-	3/300	3/300
		2	-	1/150	-
Ceará -CE	J3	1	-	1/150	1/50
Maranhão-MA	J4	1	-	3/300	1/150
Paraíba-PB	J5	1	-	-	1/150
Piauí-PI	J7	1	-	3/300	1/150
Sergipe-SE	J9	1	-	1/150	1/100
TOTAL			**1/50**	**12/1350**	**8/900**
CAPACITY EXPANSION/CONTRACTION PROFILE					
Site	**Index**	**Period**	**Technology Capacity (Number of plants/Additional capacity installed, Kt/yr)**		
			Q1	**Q2**	**Q3**
Alagoas-AL	J1	29	1/100	-	-
Bahia -BA	J2	2	-	1/50	-
		5	-	1/100	-
		13		-	1/100
		35		1/-100	-
Sergipe-SE	J9	34	-	1/-100	-

Figure 7: facility location and Evolution of capacity



Investment in ethanol production capacity in J1 (Alagoas), is of the Q1 technology including one small-capacity plant installed in period 28 which is further expanded to a large capacity plant in period 29. Whereas in J2 (Bahia) plants installed comprise of one small, one medium and one large size plants of the Q2 (Corn Dry Mill pathway) technology and one small-sized, one medium-sized and one large plant of the Q3 (Flexmill pathway) technology installed in the first period while one large plant of the Q2 (Corn Dry Mill pathway) technologies was also installed in periods 2 and 6 respectively.

Results also show that two of the Q2 plants (Small and medium) installed in the first period were expanded by additional 150 kt/yr. (50 & 100 kt/yr respectively) in the second and fifth period to become large plants. However, there was a contraction of 100 kt/yr. of the large plant capacity in period 35. The small-capacity plant of the Q3 technology was expanded in period 13 to become a large-sized plant with the addition of the 100 kt/yr.

In J3 (Ceará), one large-sized plant of Q2 technology is installed in the first period, also, a small-sized plant of the Q3 (Flex-mill) technology is installed in period 1 and stays unchanged throughout the planning period. In J4 (Maranhão), one small-size, one medium-size and one large size plants of the Q2 (Corn Dry Mill pathway) and one large-capacity plant of the Q3 (Flexmill) technology respectively are installed with a total capacity of 450 Kt/yr.

In J5 (Paraíba), one large-sized plant of the Q3 technology is installed in the first period and stays unchanged throughout the planning period.

One plant of small, medium and large capacity respectively of the Q2 technology are installed in J7 (Piauí) in the first period. Furthermore, in the same period, one large capacity plant of the Q3 technology is installed adding 150 kt/yr. production capacity.

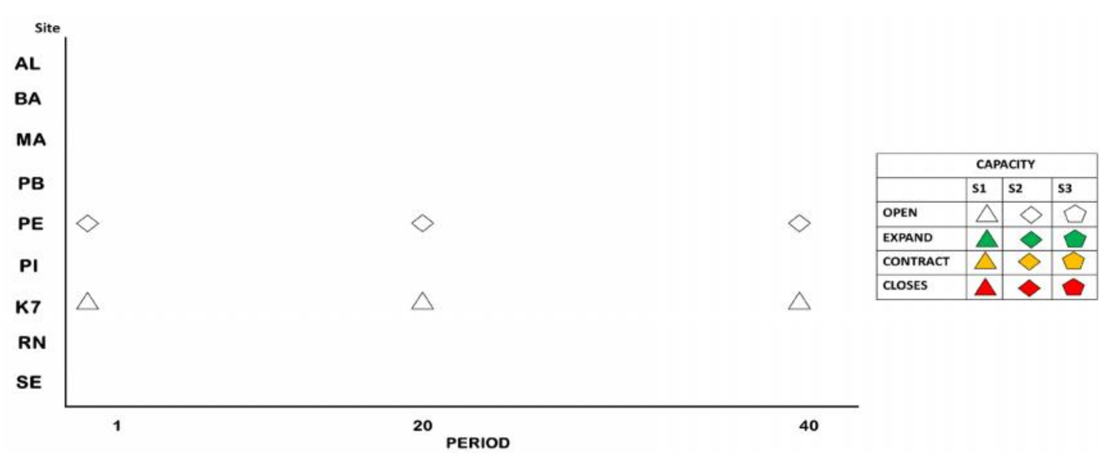
In J9 (Sergipe), one large plant of the Q2 & Q3 technology respectively are installed in period one while the Q2 plant is contracted in period 34 to a small-sized plant. There is no plant installed in J6 (Pernambuco) & J8 (RN)

At the distribution center, one small and medium blending station capacity is installed in sites K7 (Piauí) and K5 (Paraíba), respectively. The total capacity addition is 1050 Kt/yr. processing capacity to augment the blending and distribution capacity. There was no further evolution to added capacities as shown by Table 21 and Figure 8. Existing capacities were applied except for capacities and k8 (RN) and k9 (SE) which were deemed not optimal and consequently not applied in the optimal solution.

Table 21: Distribution center capacity profile

	Index	Period	Technology Capacity (Number of stations/new capacity installed, kt/yr.)
Pernambuco-PB	K5	1	1/750
Rio grande do North-RN	K7	1	1/300
Total			**2/1050**

Figure 8: Facility Location and capacity evolution of DCs



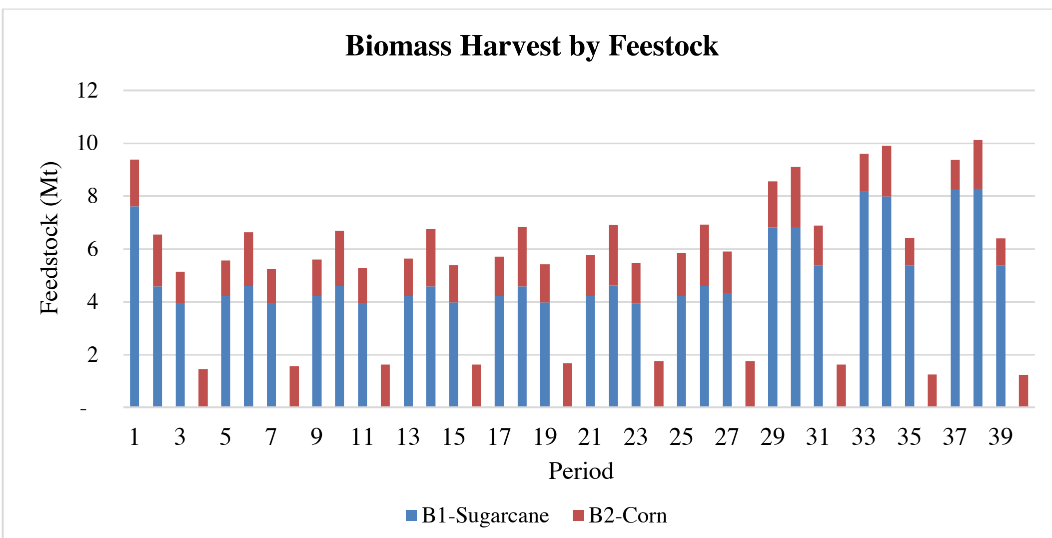
4.3.3 Supply chain components

The individual supply chain components are analyzed in this section. Each component is defined by parameters and these impact on the output of the final solutions. The components are discussed below:

4.3.3.1 Harvesting site

The amount of feedstock harvested over the planning horizon is depicted in Figure 9. These results are a derivation from the feedstock harvest variable $\boldsymbol{b} \quad _{b}$. The Figure shows that sugarcane is still the major feedstock for the production of ethanol owing to its relatively cheaper cost. Corn, on the other hand, is also harvested in all periods to augment ethanol production from sugarcane especially in periods when there is no sugarcane harvest as in periods 4, 8, 12, 16, 20, 24, 28, 32, 36 and 40. The pattern observed in this Figure mimics the seasonality of the feedstocks.

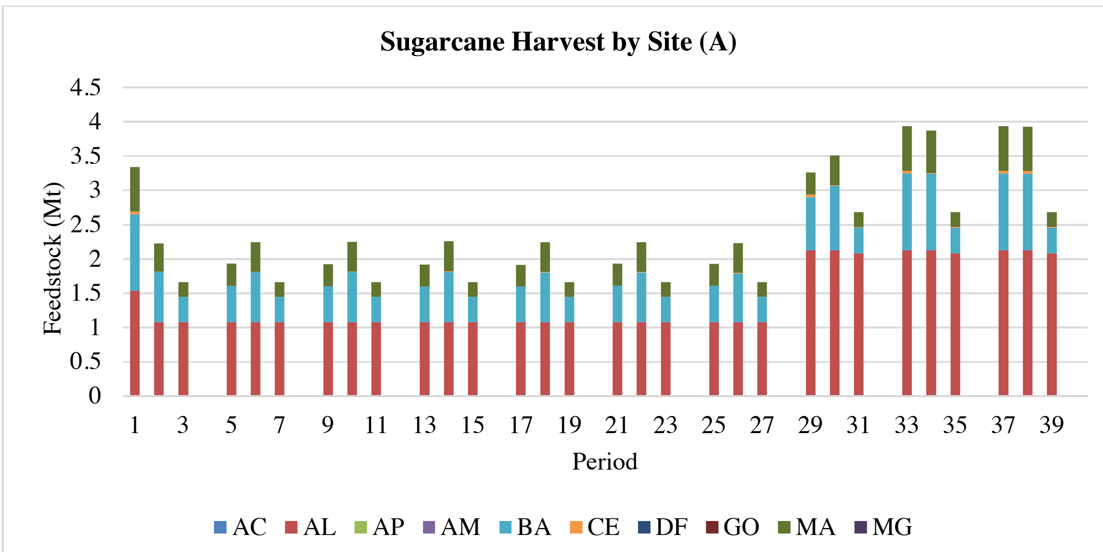
Figure 9: Biomass Harvest by Feedstock type

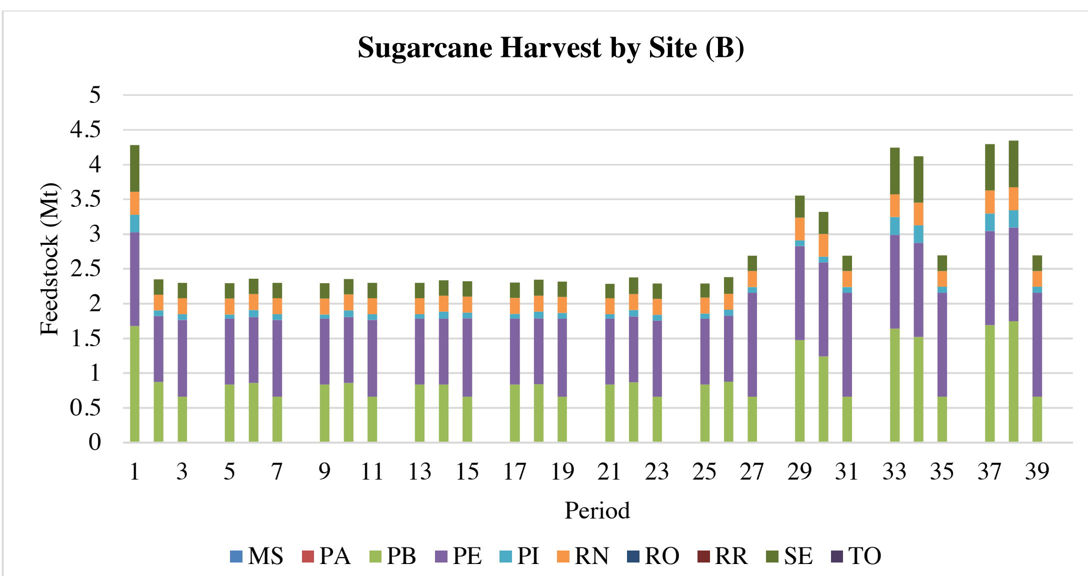


Comparative analysis of the available feedstock for harvest and actual biomass harvest as shown in Appendix D, shows that in general there is high sugarcane production potential within the region as compared to corn. However, this comparative analysis shows low level of harvest of sugarcane only achieving up to 27% of available biomass as highest percentage harvest for sugarcane as compared to corn harvest achieving up to 97% harvest from available biomass. This is largely due to the preference for corn ethanol production in this case study.

Figure 10 shows the harvests of sugarcane from each harvesting sites and their various contribution. We observe that the greatest harvest contributions come from H2 (Alagoas), H14 (Pernambuco), H13 (Paraíba), H5 (Bahia) and H9 (Maranhão) in order of relative contributions. These sites combined provide over 85% of the total biomass used in sugarcane ethanol production in plants. This is because of their relative proximity to their biorefinery site of supply. Also contributing to their selection is their relatively high feedstock productivity per hectare and the large available cultivable land as obtained from Tables 1 and 3 above. The detailed production profile for sugarcane is given in Appendix E.

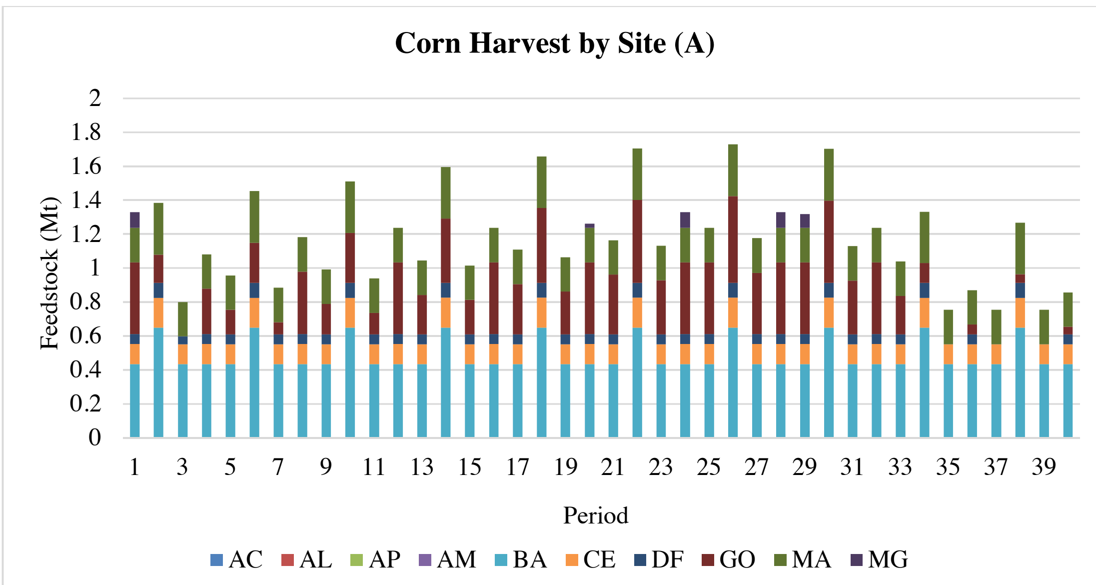
Figure 10: Sugarcane Harvest by Harvesting Site

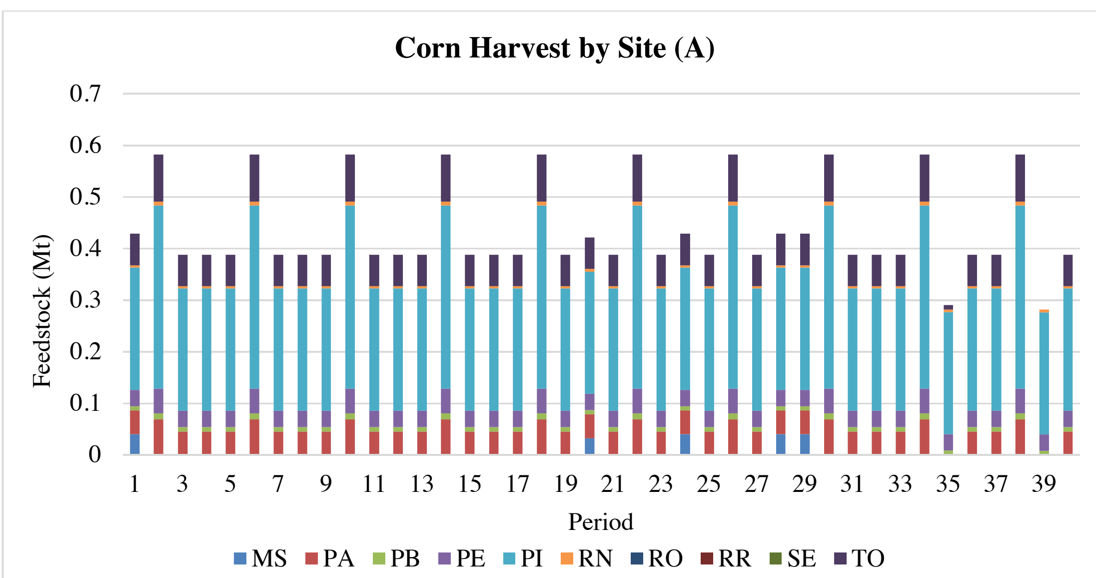




Corn harvest (Figure 11) is majorly from sites H5 (Bahia), H15 (Piauí), H9 (Maranhão), H8 (Goias) and H6 (Ceará) in order of highest contributions. These locations produce over 85% of the corn requirement for the respective biorefinery supply locations. However, we observe that harvest is also made from sites outsides the region of study, this is because of the relatively lower productivity and available land of the locations within the region (Tables 1 & 3) while also factoring proximity. Also observed is that harvest follows the production patterns modelled. The detailed production profile for corn is given in Appendix F.

Figure 11: Corn Harvest by the Production site





4.3.3.2 Biofuel production

Biomass consumed by the production pathways as given in Figure 12, shows that there is high sugarcane consumption as already indicated by the feedstock harvest profile in Figure 9. The autonomous sugarcane pathway (Q1) consumes over 70% of the total biomass in all periods of its use for biofuel production, while the Dry mill and flex mill pathways represent about 30% of production. However, when Figures 13 and 13 are compared, we observe that actual biofuel production from the autonomous biorefinery (including existing production from sugarcane) accounts for about 31% of total biofuel produced while Dry mill and flex mill production accounts for 56% and 13%, respectively.

To exemplify this, in periods 1 and 2, where we have significant sugarcane consumption and then a reduction in sugarcane consumed in the subsequent period, there is less product of biofuel in period 1 while the reduction in sugarcane production and moderate increase consumption the following period brings about a significant increase in biofuel produced. This is owing to the yields of corn to that of sugarcane as shown in Table 6. Hence, low biofuel yielding feedstock (sugarcane) requires more feedstock consumption to produce a unit quantity of biofuel whereas higher biofuel yielding feedstock requires less feedstock consumption to produce a unit quantity of biofuel.

Figure 12: feedstock consumption by production technology

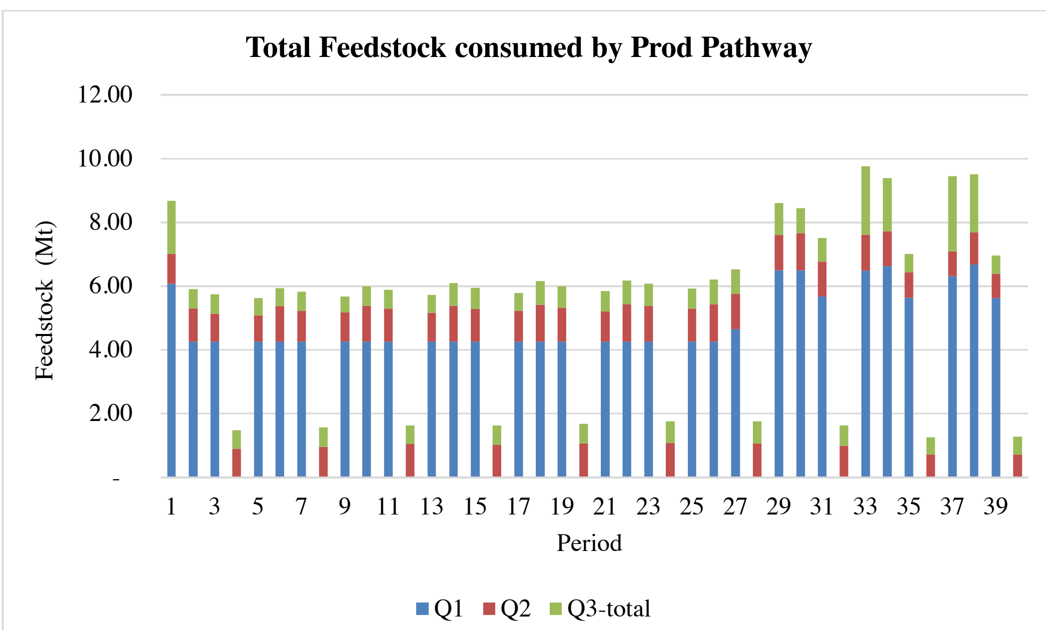
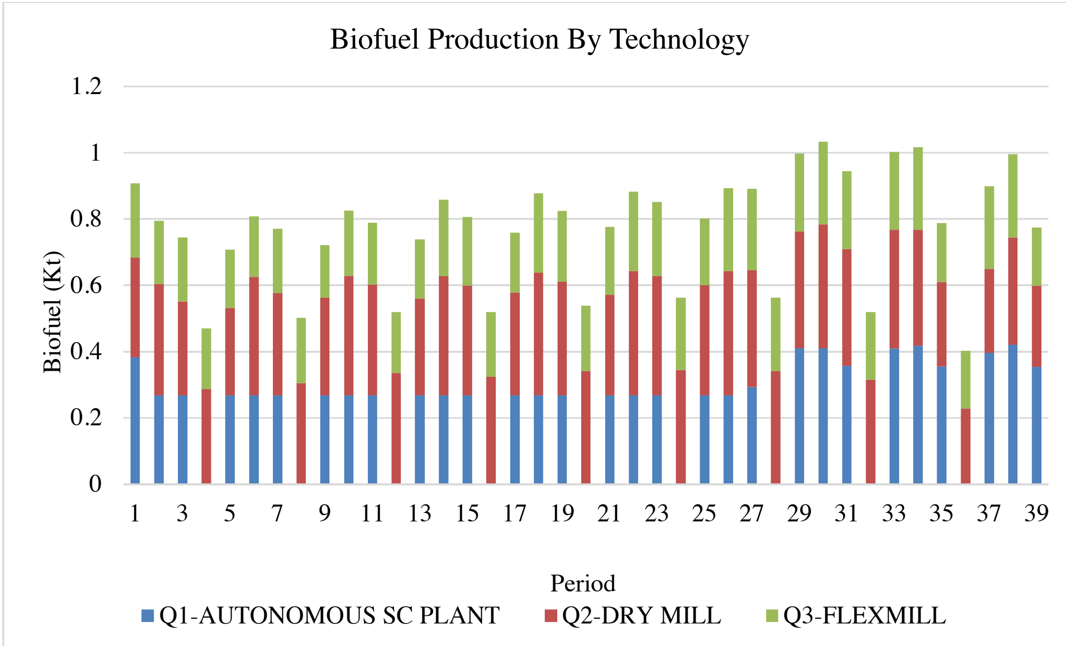


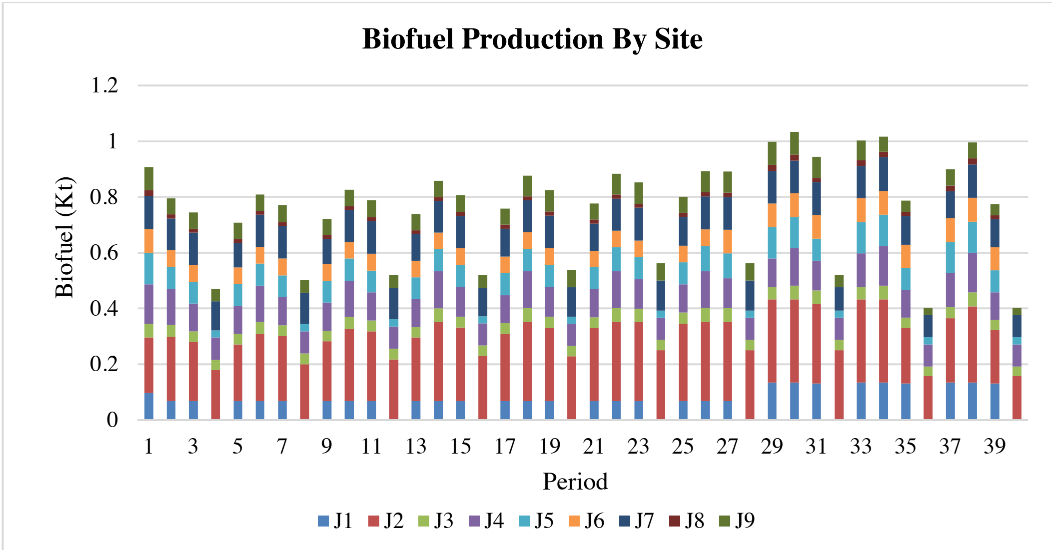
Figure 13: Biofuel production by technology



Analysis of the production by biorefinery sites shows that J2 (Bahia) has the highest production (32% of total production), 14% of total production comes from J7 (Piauí), 14% from J4 (Maranhão), 10% from J5 (Paraíba), 9% from J1 (Alagoas), 7% from J6 (Pernambuco), 8% from J9 (Sergipe), 6% from J3 (Ceará) and 2% from J8 (Rio Grande do Norte). This production profile is due to the significant investments in the dry mill and flex mill plants which augment existing sugarcane production capacity in the locations except for J1 (Alagoas) with one autonomous sugarcane plant and J8 (Rio Grande do Norte) where no new plant capacity was added.

Furthermore, when this production profile is compared to existing production profile (Table 5), we observe that J1 (Alagoas) which had the highest production now becomes one of the least production sites while J2 (Bahia) now becomes the highest production location, J3 (Ceará) which initially had no production capacity now has production capacity however remains one of the least production locations.

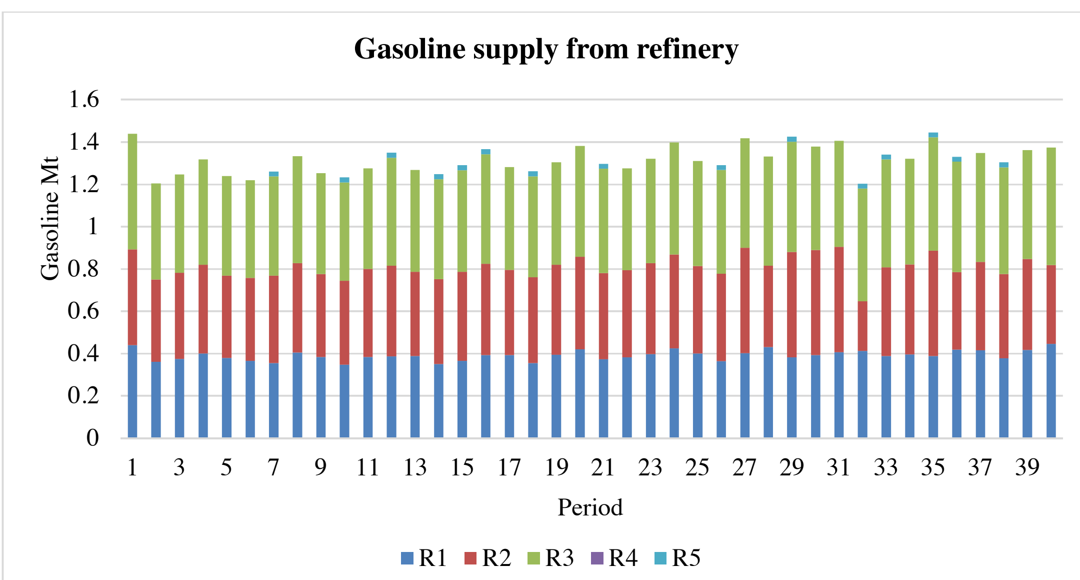
Figure 14: Biofuel production by site



4.3.3.3 Petroleum supply

Gasoline supply from refineries as shown in Figure 15 is majorly from R3 (Araucária-PR), R1 (São Francisco do Conde-BA) and R2 (Guamaré-RN) refineries which produce 99% (38%, 32% & 29% respectively) of the gasoline requirement for blending stations. This is owing to their large capacities and relative proximity to the supply locations

Figure 15: Gasoline supply from refineries

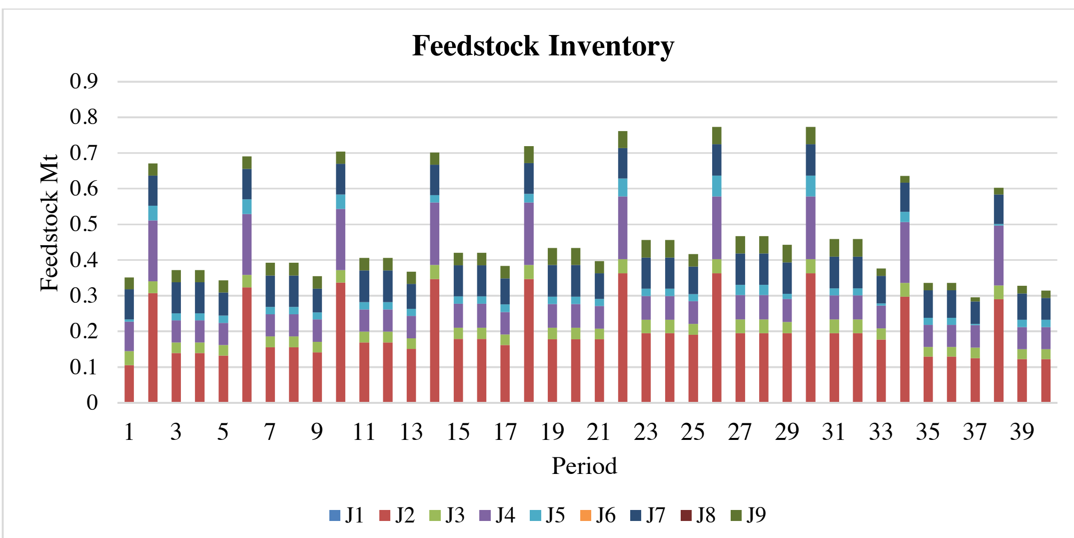


4.3.3.4 Feedstock and product inventories

Feedstock inventory maintained at the biorefinery sites is given by Figure 16. Inventory maintained at the sites only includes corn because sugarcane is perishable hence cannot be stored. However, we observed that production patterns are highly influenced by the pattern of feedstock inventory. In periods of high corn inventory, there is also high production of biofuel and vice versa when Figures 12 and 15 are compared. This pattern implies the significant contribution of corn to equalization of biofuel demand and that of maintaining feedstock inventory.

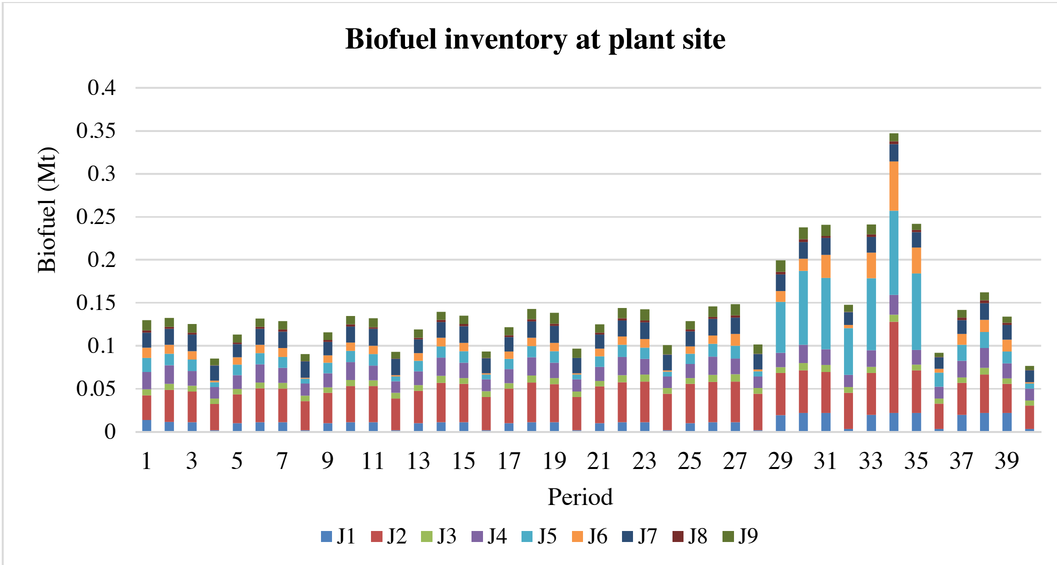
However, a downward trend is observed from periods 29 to 40, owing to the investments in Q1 plants thereby increasing sugarcane consumption coupled with high inventories at the plant site and distribution center thereby bringing about a reduction in corn consumption.

Figure 16: Feedstock inventory at biorefinery sites



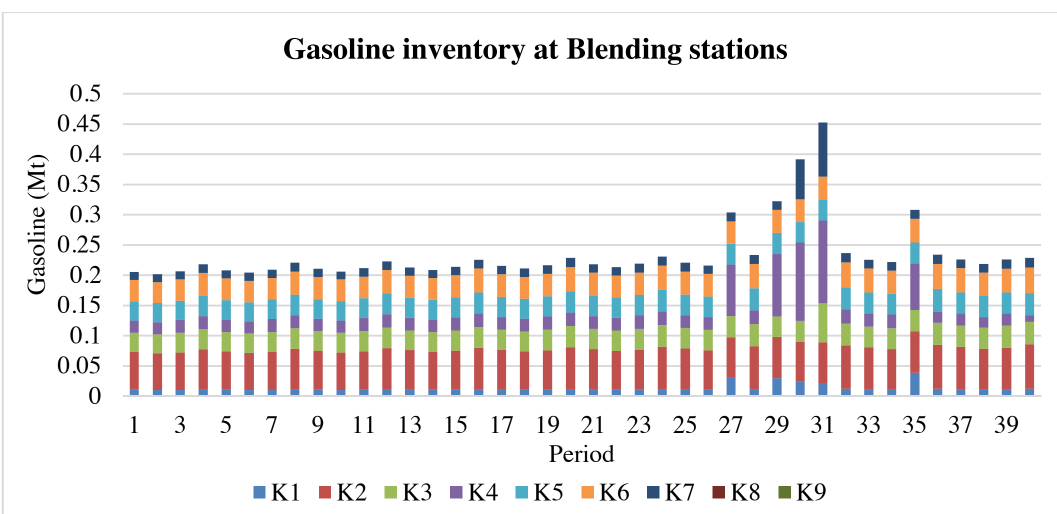
Biofuel inventory maintained at biorefineries significantly also follows production patterns and low inventory is maintained in most periods except for periods 29 to 35 where high inventories are observed. This variation is due to the accumulation of product inventories in J1, J5 & J6. It is observed that site J1 has increased production due to capacity addition while site J5 maintains its production levels but lower product flows to distribution center during this same period leading to high plant inventory levels when Figure 17 is compared with Figure 13. Inventory at the plant sites reduces back to normal levels as production reduces and inventory flows to the DCs.

Figure 17: Biofuel inventory at the biorefinery site



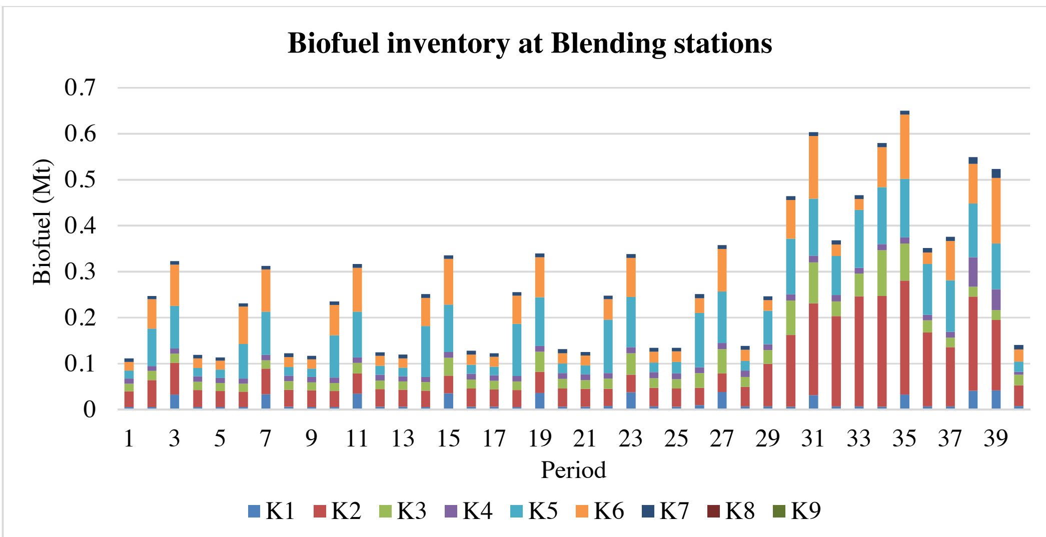
Gasoline inventory maintained at the distribution center given by Figure 18 is seen to follow the production patterns and when compared with production (Figure 14). Inventory maintained show coherence with Figure 19 as it shows that sites with the highest production (K2, K6, K3 & K5) also had the highest inventories. Inventory is significantly low for the most part when compared with production levels, however, in periods 27-35 where higher inventory levels are observed, we also observed a gradual decline in production (Figure 14) as well.

Figure 18: Gasoline inventory at blending stations



Biofuel inventory at the blending station as shown in Figure 19 also follows the production trend with high inventories maintained in high production period. However, low inventories are generally maintained owing to increasing consumption rate while also preferring production to inventory management of biofuel in DCs. Also observed is the trend of maintenance of high inventories in preceding periods to periods of sugarcane off-seasons. As explained above inventory levels grow significantly in the terminal periods due to increased production levels at the plants and also increased flow of biofuel inventory from the plants to the DCs.

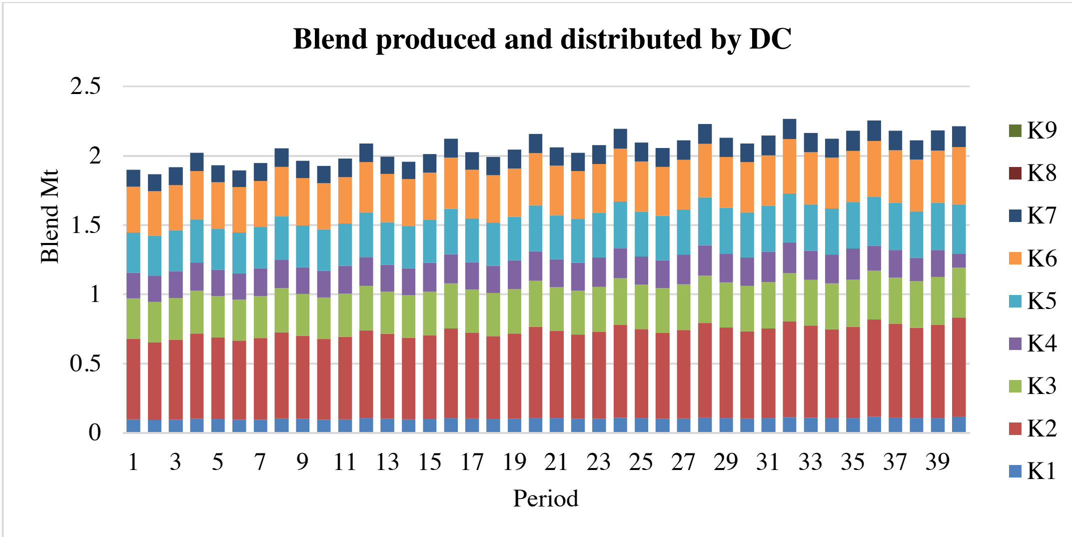
Figure 19: Biofuel inventory at Blending stations



4.3.3.5 Fuel distribution

Blend distribution profile is shown in Figure 20 below. It is observed that the profile follows the trend of demand except for the period where there was unmet demand as shown in Figure 20. The Figures show that the sites with the highest production are K2 (Bahia), K6 (Pernambuco), K3 (Ceará) and K5 (Paraíba) which produce and distribute 80% (31%, 17%, 16% & 16% respectively) of the total output for the blending stations whereas the remaining 20% was produced and distributed by K1(Alagoas), K4 (Maranhão) and K7 (Piauí). K8 and K9 do not produce blends as the optimal solution deems capacity investment, for existing and new capacity, not to be optimal.

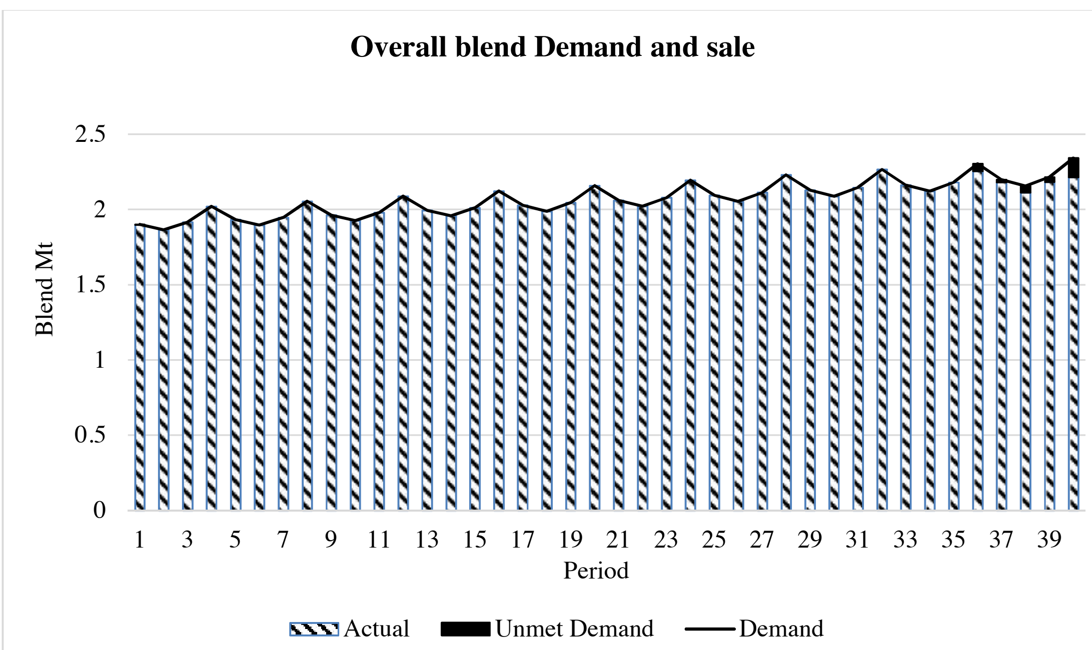
Figure 20: Blend distribution by blending station/distribution center



4.3.3.6 Demand satisfaction

Blend Sales profile to meet demand is given by Figure 21 below which shows that demand is significantly met in all periods except for periods 36 to period 40 where there is unmet demand.

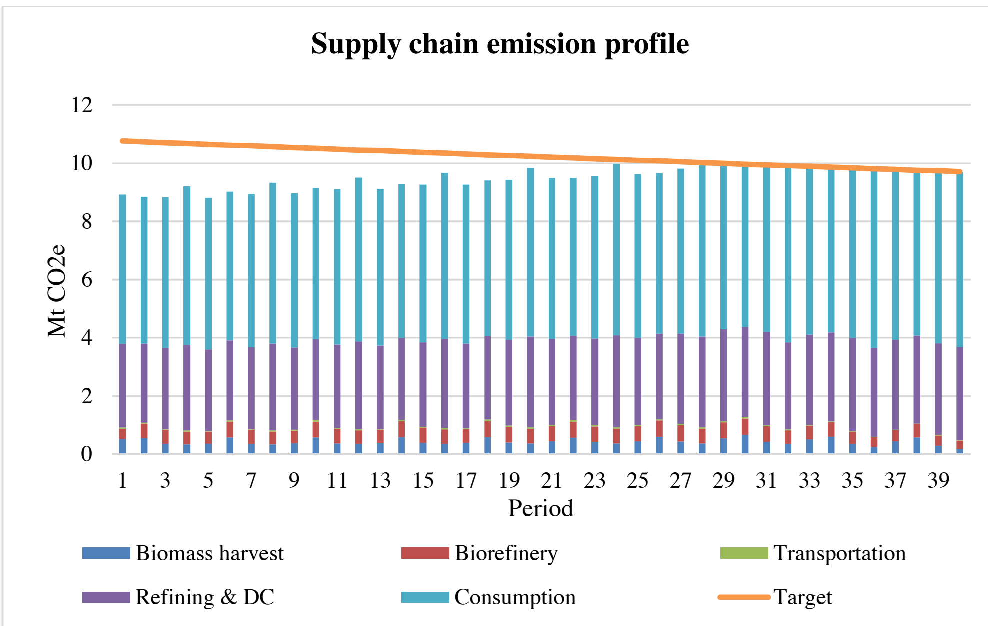
Figure 21: Overall blend Demand and sales profile

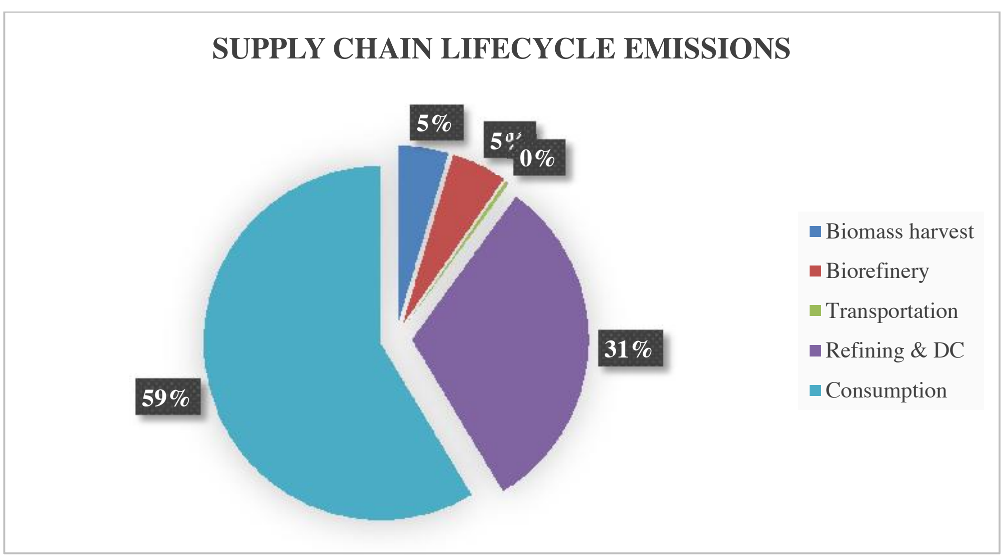


4.3.4 Supply chain emission profile

Supply chain lifecycle emissions profile in this case study is given by Figure 22. It shows compliance with periodic emission reduction targets and also emission savings concerning the targets in certain periods. While lifecycle emissions shows the most significant emissions are from the refineries, DC and fuel combustion by cars while emissions from biorefineries are the lower in comparison, corn processing mills produce the greatest emissions from the biorefineries. At the harvest site, emission from the corn cultivation and harvest is also greater than emission from sugarcane cultivation.

Figure 22: Supply chain emission profile and lifecycle emissions

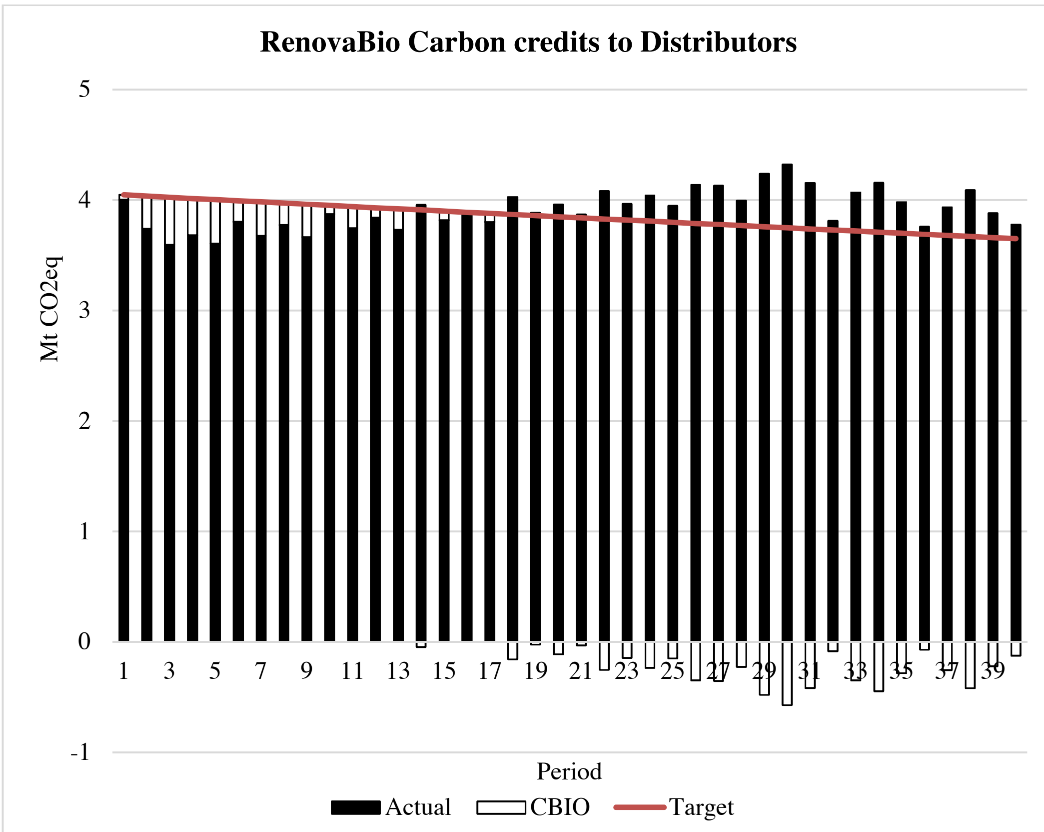




4.3.5 Carbon credits to distributors profile

Carbon credits profile due to distributors is shown in Figure 23 below. The trend of emission credit is highly influenced by the refinery emissions as periods with negative carbon credits are periods with significant refinery production as well when compared with Figure 14.

Figure 23: RenovaBio Carbon credits to Distributors



4.3.6 Sensitivity analysis

Sensitivity analysis carried out on this model involving analysis of the impact of price, feedstock, demand, and sustainability limit change on the production and plant configurations. Furthermore, a comparison between capacity utilization is also done between the dynamic capacity strategy and the traditional method. The scenarios considered are enumerated in Table 22:

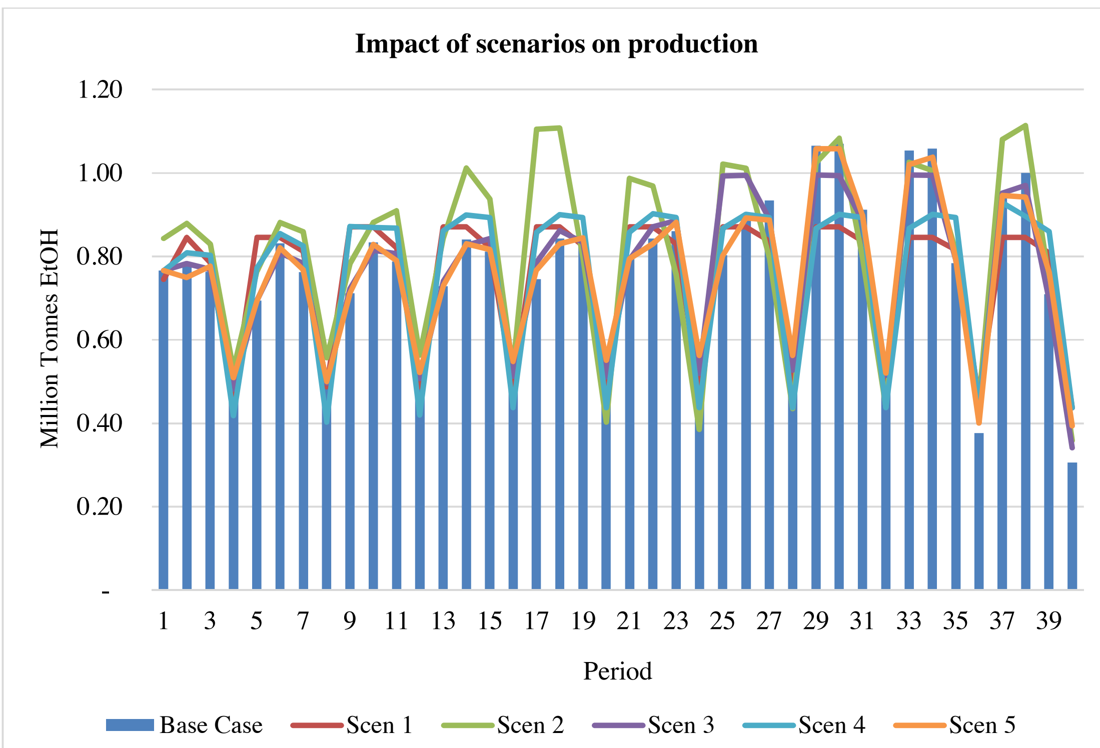
Table 22: Scenarios for sensitivity analysis

Scenario	Description
Base case	Business as usual
Scenario 1	30% price reduction
Scenario 2	10% increase in demand
Scenario 3	10% reduction in available feedstock
Scenario 4	30% reduction in sustainable harvest limit
Scenario 5	Traditional capacity strategy

4.3.6.1 Impact on Production

Production levels can be significantly affected by several factors such as feedstock availability, demand and price. Sensitivity on the production of ethanol is examined and results for different scenarios is presented in Figure 24 below:

Figure 24: Impact of scenarios on production



The base case represents the business as usual case where all parameters in the foregoing remain constant and serves as the reference base for analysis. In scenario 1 where product price is reduced by 10%, we observe that production levels stay fairly the same as the base case implying that a little impact of the price change on production levels.

On the other hand, scenario 2 with a 10% increase in demand also shows an increased production over and above the base case implying that demand still plays an important role in determining demand levels while in scenario 3 with a 10% reduction in feedstock availability also shows stable production levels due to inventory management.

Scenario 4 where the sustainable production limit is reduced by 30% does not also show a reduction in production levels while scenario 5 which is produced when applying the traditional capacity strategy shows a good match with the base case scenario.

4.3.6.2 Impact on facility configurations

Biorefinery configuration refers to the distribution of the technology decisions in the optimal solution. Results in Table 23 represent plants installed in each scenario without accounting for their evolution over horizon. However, the latter will be discussed alongside presented results.

Table 23: Sensitivity on Biorefinery configurations

Technology	Q1			Q2			Q3		
Scenario	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Base case	1	-	-	3	3	6	2	2	4
Scenario 1	-	-	-	7	5	4	2	2	4
Scenario 2	-	-	2	1	2	3	2	1	5
Scenario 3	-	-	-	2	3	6	1	4	5
Scenario 4	-	-	-	1	1	3	2	3	3
Scenario 5	-	-	1	3	3	7	2	1	5

As already established, more investment is made in plants with corn processing ability, i.e. Q2 and Q3 pathways. Comparing scenario 1 to the base case, we observe that lower price of a product affects the choice of processing pathway as the results show no investment in the Q1 technology and investment in Q3 technology stays the same significantly while the Q2 technology increases by four small-sized plants, two medium-sized plant but decreases by two large size plants with respect to the base case. This implies that in low price scenarios establishing new Q1 plants will not be optimal.

When demand is increased by 10%, the number of plants also increases by two large plants in the Q1 technology while there are significant changes in the configuration of the Q2 and Q3 technologies in comparison to the base. Although the overall the configuration does not change significantly it can be also observed that higher demand also requires investments in larger plants however there results had a high optimality gap which portends it can be improved.

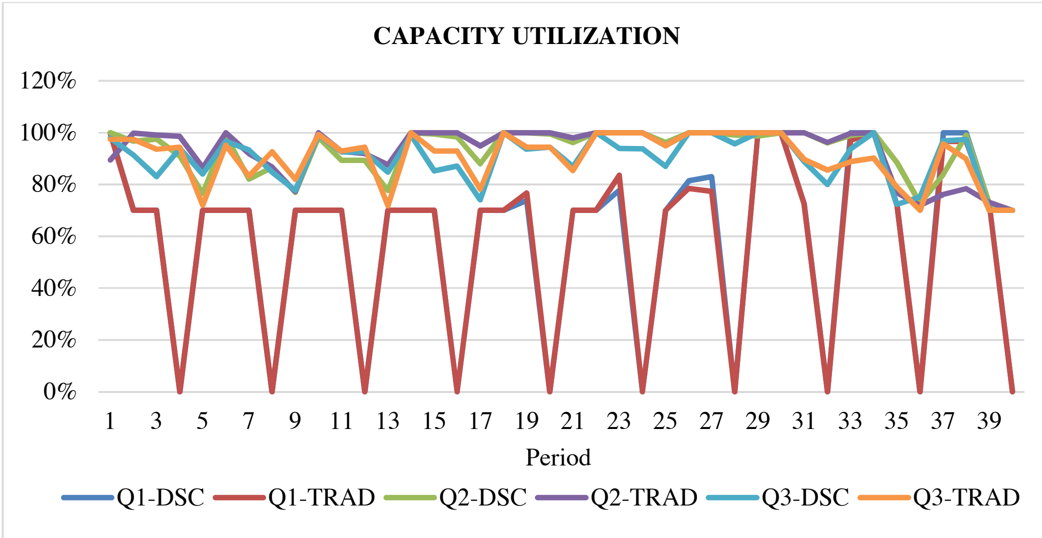
Scenarios 3 and 4 are related to changes in feedstock availability and can be seen that in scenario 3 the Q1 technology configuration stays same as the base case, one small plant of the Q2 technology is reduced with regards to the base case and in the Q3 technology, there is a reduction of one small plant, addition of two medium and one plants respectively. In scenario 4 where the sustainable harvest limit is reduced by 30%, it is observed that there was no Q1 plant installed, however, Q2 and Q3 technology reduced in number in comparison to the base. These trends show the impact of sugarcane seasonality and availability on technology choice.

Scenario 5 when compared with the base case, shows fairly same configuration when the evolution of installed capacities of the base are taken into consideration which implies total production capacity is not changed but DSC method gives a more realistic investment plan for capacity changes over time.

4.3.6.3 Capacity utilization comparison of dynamic capacity strategy (DSC) and traditional method (TRAD)

Capacity utilization is the ratio of actual plant production to installed capacities. This serves to measure the asset turnover ratio (ATR) which refers to the efficiency of use of investment. Comparing the three (3) production pathways shown in Figure 25, we observe that the Q1 pathway has the lowest capacity utilization which is approximately 70% for most periods while Q2 and Q3 pathways have capacity utilization greater than 85% for most periods indicating a preference for the production of corn ethanol.

Figure 25: Capacity utilization comparison chart for DSC and TRAD



Furthermore, the ATR for the DSC and TRAD when comparing the Q1 pathway, are observed to remain the same except for certain periods where the DSC exceeds the TRAD. Comparing the ATR for the Q2 pathway shows TRAD has higher ATR in some periods but both DSC and TRAD were mostly over 90% capacity utilization while the ATR for the Q3 pathway shows that for the most part, the TRAD capacity utilization is higher than the DSC.

5 Conclusion and Recommendations

This study presented a realistic investment decision-making tool which includes strategic and tactical level decisions into the design of an integrated biofuel and petroleum supply chain to aid in the decision-making process for policymakers and potential investors. The foregoing has reviewed various approaches adopted by several researchers on biofuel supply chain planning and established an existing paucity of designs that integrates existing petroleum infrastructure network while also considering facility capacity dynamism and national/sectoral emission reduction targets.

A MILP optimization model was built to determine the technology, location, capacity and number of biorefineries and distribution centers. Feedstock seasonality every quarter was also considered to investigate inventory management practice on satisfying demand. Model constraints included biomass feedstock availability at each harvesting sites, product demand at each demand location, the amount of feedstock, investment budget, production constraints, national emission reduction targets. Also taken into consideration were the existing production capacities of biorefineries and petroleum refineries seldom considered in planning efforts.

The model was validated using the trivial validation method and a case study in the Northeast of Brazil considering sugarcane and corn feedstock alternatives and automous sugarcane plant, corn dry mill ethanol plant and flex mill plant technology alternatives. The RenovaBio carbon trading strategy was also applied to determine carbon credits due to fuel distributors as a result of meeting their emission reduction targets.

The results of the case study showed that although sugarcane was consumed more, its low conversion efficiency made it unpreferable for future investments and most investments were of corn Dry mill plants and flex mill plants with the former having the highest contribution. The seasonality and storability of corn also make it available for all year round production even though sugarcane ethanol can be stored as well. Most plants were also observed to be established in Bahia making it the desired location for more investments. There were no significant investments in blending distribution centers owing to the already existing large capacity. Also, the new facilities did not evolve with time in terms of capacity expansion (Contraction) or closure.

Sensitivity analysis on the model showed no significant impacts of price, feedstock availability and traditional capacity strategy on production patterns, however, demand impacted on production levels. The supply chain configuration was affected by changes in feedstock levels and demand but a comparison between the traditional and dynamic capacity strategy showed no difference except for the evolution with time.

Although lifecycle emissions from the entire supply chain are below the national target levels, carbon credits to distributors vary over time and this trend was observed to be highly influenced by refining emissions. Supply chain emissions had the highest contributions from refining and fuel combustion emissions in cars. Hence, efficiency improvements in petroleum refining and internal combustion engine systems could also improve the achievement of reduction targets faster.

In view of the foregoing, policy makers may promote investments in corn processing mills and flex mills for market equalisation and production growth within the region and incentivise efficiency improvement and carbon emiison reduction in the petroleum refining and internal combustion engine systems to accelerate achievement of redcution targets.

In line with the RenovaBio vision of incentivising distributors and biorefineries to adopt more efficient production processes/pathways and feedstocks, future studies may consider the integration of efficiency improvement to supply chain designs. Furthermore, a nationwide case study considering monthly periods for feedstock production would add more realism to the planning effort. Investigation of feedstock alternative uses and export of feedstock and product would also better present the market dynamics to the model. The model could be further extended to include variation second-generation production technologies, feedstock gathering centers and upstream petroleum activities as well.

In conclusion, this contribution provides a new paradigm for considering biorefinery supply chain planning considering feedstock resource planning, capacity planning, integration with petroleum supply chain, and supply chain economics. Finally, this contribution provides a more holistic, interdisciplinary way of planning the biorefinery industry from harvesting site to final consumption.

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APPENDIX A - Fuel consumption data

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
d1	97,919	93,387	94,695	102,090	99,487	94,876	96,219	103,767	101,080	96,388	97,768	105,474	102,699	97,926	99,342
d2	496,356	479,413	494,605	526,111	504,555	487,337	502,889	535,029	512,895	495,398	511,319	544,106	521,379	503,598	519,897
d3	291,518	292,545	300,641	311,303	296,199	297,245	305,477	316,331	300,958	302,023	310,394	321,444	305,796	306,881	315,392
d4	185,973	185,458	196,465	200,834	188,841	188,320	199,506	203,940	191,754	191,227	202,595	207,095	194,713	194,179	205,733
d5	154,941	153,762	154,670	164,314	157,495	156,282	157,204	167,085	160,094	158,844	159,781	169,906	162,737	161,451	162,402
d6	329,430	321,282	325,579	349,949	334,868	326,610	330,994	355,893	340,400	332,030	336,504	361,943	346,028	337,545	342,111
d7	121,656	120,806	127,212	130,927	123,565	122,702	129,226	133,017	125,504	124,628	131,273	135,141	127,475	126,585	133,353
d8	138,823	137,370	140,380	147,661	141,050	139,561	142,625	150,061	143,313	141,789	144,906	152,502	145,614	144,054	147,226
d9	85,257	81,913	82,400	87,931	86,611	83,203	83,700	89,356	87,986	84,514	85,021	90,805	89,384	85,846	86,363

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
d1	107,209	104,346	99,489	100,943	108,975	106,020	101,078	102,571	110,771	107,722	102,693	104,226	112,598	109,452	**104,335**
d2	553,345	530,011	511,941	528,628	562,751	538,792	520,429	537,512	572,325	547,726	529,064	546,554	582,071	556,815	**537,850**
d3	326,642	310,714	311,820	320,474	331,928	315,715	316,842	325,642	337,303	320,799	321,947	330,895	342,768	325,968	**327,138**
d4	210,300	197,718	197,177	208,920	213,555	200,770	200,223	212,158	216,861	203,870	203,316	215,446	220,220	207,019	**206,458**
d5	172,777	165,427	164,102	165,067	175,699	168,162	166,798	167,779	178,673	170,946	169,541	170,537	181,700	173,777	**172,332**
d6	368,102	351,754	343,156	347,815	374,371	357,578	348,865	353,620	380,753	363,504	354,673	359,526	387,251	369,533	**360,583**
d7	137,300	129,477	128,574	135,467	139,495	131,512	130,596	137,616	141,726	133,579	132,649	139,799	143,994	135,680	**134,736**
d8	154,983	147,954	146,355	149,583	157,507	150,332	148,695	151,980	160,074	152,750	151,074	154,417	162,684	155,208	**153,492**
d9	92,279	90,805	87,200	87,726	93,777	92,250	88,575	89,113	95,301	93,718	89,973	90,521	96,851	95,210	**91,394**

	31	32	33	34	35	36	37	38	39	40
d1	105,909	114,456	111,211	106,004	107,620	116,347	112,999	107,700	109,360	118,270
d2	555,756	591,993	566,063	546,789	565,121	602,094	575,472	555,883	574,653	612,376
d3	336,237	348,325	331,224	332,416	341,668	353,977	336,568	337,782	347,191	359,723
d4	218,787	223,631	210,217	209,650	222,181	227,096	213,466	212,891	225,628	230,616
d5	173,343	184,782	176,658	175,170	176,197	187,918	179,589	178,057	179,100	191,111
d6	365,536	393,865	375,667	366,597	371,652	400,599	381,907	372,716	377,875	407,455
d7	142,019	146,300	137,815	136,857	144,274	148,643	139,984	139,011	146,567	151,026
d8	156,894	165,339	157,707	155,950	159,413	168,039	160,248	158,449	161,973	170,785
d9	91,953	98,427	96,726	92,838	93,407	100,029	98,268	94,305	94,886	101,659

ANNEX A - Spatial Data

Rio Grande do Sul	G21	0																				
Paraná	G20	705	0																			
São Paulo	G19	1101	405	0																		
Sergipe	G18	3233	2536	2128	0																	
Rio Grande do Norte	G17	3993	3926	2888	774	0																
Piauí	G16	3712	3015	2634	1089	1079	0															
Pernambuco	G15	3716	3019	2611	497	287	1118	0														
Paraíba	G14	3830	3134	2725	612	190	1152	123	0													
Maranhão	G13	3828	3165	2958	1562	1413	429	1546	1579	0												
Ceará	G12	4029	3333	2924	1124	536	577	804	709	877	0											
Bahia	G11	3043	2346	1938	322	1084	1143	805	921	1571	1229	0										
Alagoas	G10	3482	2785	2377	263	540	1107	261	377	1535	573	963	0									
Roraima	G09	5423	4760	4688	5294	5330	4260	5278	5311	4272	4833	5301	5266	0								
Rondônia	G08	3761	3097	3025	4025	4061	2991	4009	4042	3003	3564	3887	3997	1664	0							
Pará	G07	3806	3142	2935	2040	1984	906	2023	2057	797	1482	2046	2011	3859	2590	0						
Amazonas	G06	4645	3982	3910	4516	4551	3482	4499	4533	3494	4055	4523	4488	780	885	3081	0					
Amapá	G05	4272	3609	3402	2811	2756	1678	2795	2828	1569	2254	2818	2783	4269	3000	887	3491	0				
Acre	G04	4261	3598	3526	4532	4568	3498	4516	4549	3510	4071	4388	4504	2171	505	3097	1392	3507	0			
Mato Grosso do Sul	G03	1454	1004	1008	2593	3266	2677	3075	3192	2821	3108	2404	2842	3778	2115	2791	3000	3151	2616	0		
Mato Grosso	G02	2148	1676	1532	2655	3427	2452	3138	3254	2595	3025	2466	2925	3075	1411	2469	2296	2829	1912	702	0	
Goiás	G01	1831	1167	930	1847	2521	1854	2330	2447	1998	2283	1636	2097	3968	2304	1976	3189	2441	2806	826	892	0
		G21	G20	G19	G18	G17	G16	G15	G14	G13	G13	G12	G11	G09	G08	G07	G06	G05	G04	G03	G02	G01

Source: KOSTIN et al., (2018)

APPENDIX B - Trivial Validation results

Period (Quarter)	Feedstock Harvest (t/quarter)		Feedstock Inventory (t/quarter)		Total Feed Processed (t/quarter)						Biofuel Produced (t/quarter)			Feedstock processing validation (t/quarter)
					Q1		Q2		Q3		Q1	Q2	Q3	
	B1	B2	B1	B2	B1	B2	B1	B2	B1	B2				
1	766,503.11	-	-	-	766,503.11	-	-	-	-	-	766,503.11	-	-	-
2	943,063.18	-	-	-	943,063.18	-	-	-	-	-	943,063.18	-	-	-
3	1,061,663.31	-	-	-	1,061,663.31	-	-	-	-	-	1,061,663.31	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	749,291.37	-	-	-	749,291.37	-	-	-	-	-	749,291.37	-	-	-
6	936,215.84	-	-	-	936,215.84	-	-	-	-	-	936,215.84	-	-	-
7	1,096,945.44	-	-	-	1,096,945.44	-	-	-	-	-	1,096,945.44	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	775,541.37	-	-	-	775,541.37	-	-	-	-	-	775,541.37	-	-	-
10	978,864.89	-	-	-	978,864.89	-	-	-	-	-	978,864.89	-	-	-
11	1,096,945.69	-	-	-	1,096,945.69	-	-	-	-	-	1,096,945.69	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	775,541.55	-	-	-	775,541.55	-	-	-	-	-	775,541.55	-	-	-
14	1,024,498.85	-	-	-	1,024,498.85	-	-	-	-	-	1,024,498.85	-	-	-
15	1,121,945.69	-	-	-	1,121,945.69	-	-	-	-	-	1,121,945.69	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	793,041.55	-	-	-	793,041.55	-	-	-	-	-	793,041.55	-	-	-
18	1,041,916.10	-	-	-	1,041,916.10	-	-	-	-	-	1,041,916.10	-	-	-
19	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	819,291.55	-	-	-	819,291.55	-	-	-	-	-	819,291.55	-	-	-

Period (Quarter)	Feedstock Harvest (t/quarter)		Feedstock Inventory (t/quarter)		Total Feed Processed (t/quarter)						Biofuel Produced (t/quarter)			Feedstock processing validation (t/quarter)
22	1,089,912.55	-	-	-	1,089,912.55	-	-	-	-	-	1,089,912.55	-	-	-
23	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25	823,663.49	-	-	-	823,663.49	-	-	-	-	-	823,663.49	-	-	-
26	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
27	1,161,663.56	-	-	-	1,161,663.56	-	-	-	-	-	1,161,663.56	-	-	-
28	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	901,711.52	-	-	-	901,711.52	-	-	-	-	-	901,711.52	-	-	-
30	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
31	1,161,663.56	-	-	-	1,161,663.56	-	-	-	-	-	1,161,663.56	-	-	-
32	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33	981,734.49	-	-	-	981,734.49	-	-	-	-	-	981,734.49	-	-	-
34	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
35	1,161,663.56	-	-	-	1,161,663.56	-	-	-	-	-	1,161,663.56	-	-	-
36	-	-	-	-	-	-	-	-	-	-	-	-	-	-
37	1,063,783.58	-	-	-	1,063,783.58	-	-	-	-	-	1,063,783.58	-	-	-
38	1,159,445.69	-	-	-	1,159,445.69	-	-	-	-	-	1,159,445.69	-	-	-
39	1,161,663.56	-	-	-	1,161,663.56	-	-	-	-	-	1,161,663.56	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Continuation

Period (Quarter)	Biofuel Inventory In Plant (t/quarter)	Biofuel Distributed To DC (t/quarter)	Biofuel Inventory At DC (t/quarter)	Biofuel Consumed At DC (t/quarter)	Gasoline Distributed To DC (t/quarter)	Gasoline Inventory At DC (t/quarter)	Gasoline Consumed At DC (t/quarter)	Blend Produced (t/quarter)	Sales (t/quarter)	Demand (t/quarter)	Unmet Demand (t/quarter)
1	51,100	715,403	47,694	667,709	1,322,321	88,155	1,234,166	1,901,876	1,901,876	1,901,876	-
2	68,194	954,713	345,956	656,451	1,207,724	86,392	1,209,487	1,865,937	1,865,937	1,865,937	-
3	95,687	1,005,423	675,690	675,690	2,395,526	1,240,959	1,240,959	1,916,648	1,916,648	1,916,648	-
4	6,379	89,308	51,000	713,998	1,373,289	1,307,124	1,307,124	2,021,121	2,021,121	2,021,121	-
5	50,378	696,383	63,216	684,167	30,559	89,179	1,248,504	1,932,671	1,932,671	1,932,671	-
6	63,323	894,139	284,730	672,625	2,357,841	1,223,510	1,223,510	1,896,135	1,896,135	1,896,135	-
7	98,245	1,100,068	692,399	692,399	121,604	89,674	1,255,440	1,947,840	1,947,840	1,947,840	-
8	6,550	91,695	52,273	731,821	1,327,460	94,476	1,322,659	2,054,480	2,054,480	2,054,480	-
9	53,889	727,044	78,280	701,037	1,258,683	90,211	1,262,948	1,963,985	1,963,985	1,963,985	-
10	100,706	929,984	319,059	689,205	2,385,062	1,237,636	1,237,636	1,926,841	1,926,841	1,926,841	-
11	100,872	1,100,001	709,530	709,530	123,110	90,716	1,270,030	1,979,560	1,979,560	1,979,560	-
12	6,725	94,148	53,579	750,099	1,343,193	95,594	1,338,316	2,088,415	2,088,415	2,088,415	-
13	53,901	754,615	89,863	718,331	2,459,398	1,277,496	1,277,496	1,995,826	1,995,826	1,995,826	-
14	133,614	895,583	279,246	706,201	63,787	89,419	1,251,864	1,958,065	1,958,065	1,958,065	-
15	103,573	1,174,921	727,074	727,093	1,287,073	91,766	1,284,726	2,011,818	2,011,818	2,011,818	-
16	6,905	96,686	54,917	768,843	1,359,049	96,721	1,354,094	2,122,937	2,122,937	2,122,937	-
17	53,913	754,785	73,644	736,058	2,487,573	1,292,147	1,292,147	2,028,205	2,028,205	2,028,205	-
18	72,522	1,014,815	364,835	723,623	64,487	90,442	1,266,191	1,989,815	1,989,815	1,989,815	-
19	106,348	1,091,173	710,911	745,098	2,508,612	1,299,527	1,299,527	2,044,625	2,044,625	2,044,625	-
20	7,090	133,445	56,290	788,066	168,321	97,857	1,369,992	2,158,058	2,158,058	2,158,058	-
21	55,092	773,568	75,627	754,231	2,515,942	1,306,900	1,306,900	2,061,131	2,061,131	2,061,131	-

Period (Quarter)	Biofuel Inventory In Plant (t/quarter)	Biofuel Distributed To DC (t/quarter)	Biofuel Inventory At DC (t/quarter)	Biofuel Consumed At DC (t/quarter)	Gasoline Distributed To DC (t/quarter)	Gasoline Inventory At DC (t/quarter)	Gasoline Consumed At DC (t/quarter)	Blend Produced (t/quarter)	Sales (t/quarter)	Demand (t/quarter)	Unmet Demand (t/quarter)
22	76,383	981,409	315,553	741,483	65,190	91,473	1,280,617	2,022,100	2,022,100	2,022,100	-
23	109,200	1,177,384	729,380	763,558	2,196,713	973,754	1,314,432	2,077,990	2,077,990	2,077,990	-
24	7,280	136,098	57,698	807,779	511,255	99,001	1,386,008	2,193,787	2,193,787	2,193,787	-
25	56,112	785,078	69,915	772,861	1,317,162	94,411	1,321,752	2,094,613	2,094,613	2,094,613	-
26	78,853	1,018,555	328,678	759,792	2,495,868	1,295,139	1,295,139	2,054,932	2,054,932	2,054,932	-
27	112,131	1,202,101	748,296	782,483	1,363,739	1,329,439	1,329,439	2,111,923	2,111,923	2,111,923	-
28	7,475	138,843	59,143	827,996	172,854	100,153	1,402,140	2,230,137	2,230,137	2,230,137	-
29	60,161	841,766	108,949	791,960	1,332,028	95,479	1,336,702	2,128,662	2,128,662	2,128,662	-
30	80,289	1,124,015	454,402	778,561	1,571,981	357,703	1,309,756	2,088,318	2,088,318	2,088,318	-
31	115,143	1,115,278	767,793	801,887	2,331,389	1,344,546	1,344,546	2,146,434	2,146,434	2,146,434	-
32	7,676	141,561	60,624	848,730	175,155	101,313	1,418,388	2,267,118	2,267,118	2,267,118	-
33	147,624	808,883	57,967	811,539	2,244,213	993,779	1,351,748	2,163,288	2,163,288	2,163,288	-
34	87,863	1,229,592	489,756	797,802	915,750	585,062	1,324,466	2,122,269	2,122,269	2,122,269	-
35	118,238	1,119,562	787,536	821,782	2,134,441	1,359,752	1,359,752	2,181,533	2,181,533	2,181,533	-
36	7,883	144,601	62,143	869,995	177,478	102,482	1,434,748	2,304,743	2,304,743	2,304,743	-
37	68,309	857,701	88,232	831,611	1,362,041	97,635	1,366,888	2,198,500	2,198,500	2,198,500	-
38	83,517	1,032,469	303,173	817,528	2,051,400	809,767	1,339,267	2,156,795	2,156,795	2,156,795	-
39	121,420	1,381,185	842,179	842,179	1,940,339	1,375,053	1,375,053	2,217,232	2,217,232	2,217,232	-
40	8,095	113,325	63,700	891,804	1,527,384	1,451,218	1,451,218	2,343,023	2,343,023	2,343,023	-

APPENDIX C - Northeast case study validation results

Period (Quarter)	Feedstock Harvest (t/quarter)		Feedstock Inventory (t/quarter)		Total Feed Processed (t/quarter)						Biofuel Produced (t/quarter)			BIOFUEL INVENTORY IN PLANT
					Q1		**Q2**		**Q3**		**Q1**	**Q2**	**Q3**	
	B1	**B2**	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**				
1	7,176,675	1,624,626	-	536,574	6,078,040	-	-	937,500	1,189,561	468,930	382,916	300,000	225,000	129,702
2	4,762,286	2,098,265	-	1,044,232	4,254,628	-	-	1,047,960	5,782	597,918	268,042	335,347	191,698	132,113
3	3,973,161	1,265,252	-	762,765	4,254,628	-	-	886,691	3,732	600,673	268,042	283,741	192,450	125,192
4	-	1,546,718	-	762,765	-	-	-	895,146	-	573,491	-	286,447	183,517	85,022
5	4,148,490	1,225,356	-	656,627	4,254,628	-	-	822,217	-	550,690	268,042	263,109	176,221	113,199
6	4,673,761	2,179,806	-	1,075,761	4,254,628	-	-	1,117,211	-	571,793	268,042	357,507	182,974	131,675
7	3,944,156	1,230,221	-	761,609	4,254,628	-	-	963,923	3,783	606,372	268,042	308,455	194,277	128,921
8	-	1,544,373	-	761,609	-	-	-	954,619	-	615,675	-	305,478	197,016	90,202
9	4,178,544	1,310,328	-	684,309	4,254,628	-	-	922,923	757	494,575	268,042	295,335	158,312	115,984
10	4,677,589	2,190,646	-	1,107,271	4,254,628	-	-	1,128,072	-	615,813	268,042	360,983	197,060	134,581
11	3,948,016	1,316,947	-	800,659	4,254,628	-	-	1,044,268	3,813	580,358	268,042	334,166	185,955	131,820
12	-	1,623,559	-	800,659	-	-	-	1,049,818	-	574,808	-	335,942	183,939	93,100
13	4,171,246	1,346,992	-	709,316	4,254,628	-	-	912,263	763	558,628	268,042	291,924	178,809	118,839
14	4,682,127	2,217,325	-	1,136,815	4,254,628	-	-	1,125,138	-	719,583	268,042	360,044	230,267	139,599
15	3,964,007	1,394,967	-	836,185	4,254,628	-	-	1,036,477	7,094	646,597	268,042	331,673	207,358	135,239
16	-	1,695,597	-	836,185	-	-	-	1,012,376	-	612,250	-	323,960	195,920	93,588
17	4,160,554	1,392,639	-	736,125	4,254,628	-	-	970,259	1,419	562,993	268,042	310,483	180,247	121,766
18	4,701,243	2,243,490	-	1,182,741	4,254,628	-	-	1,157,969	-	746,094	268,042	370,550	238,750	142,730
19	4,170,509	1,439,217	-	865,968	4,254,628	-	-	1,072,339	7,684	665,631	268,042	343,148	213,486	138,201
20	-	1,755,990	-	865,968	-	-	-	1,066,406	-	615,835	-	341,250	197,067	96,645
21	4,221,781	1,623,846	-	822,324	4,254,628	-	-	948,972	1,537	640,322	268,042	303,671	205,000	124,765
22	4,617,323	2,159,570	-	1,185,019	4,254,628	-	-	1,171,875	-	750,077	268,042	375,000	240,025	143,976

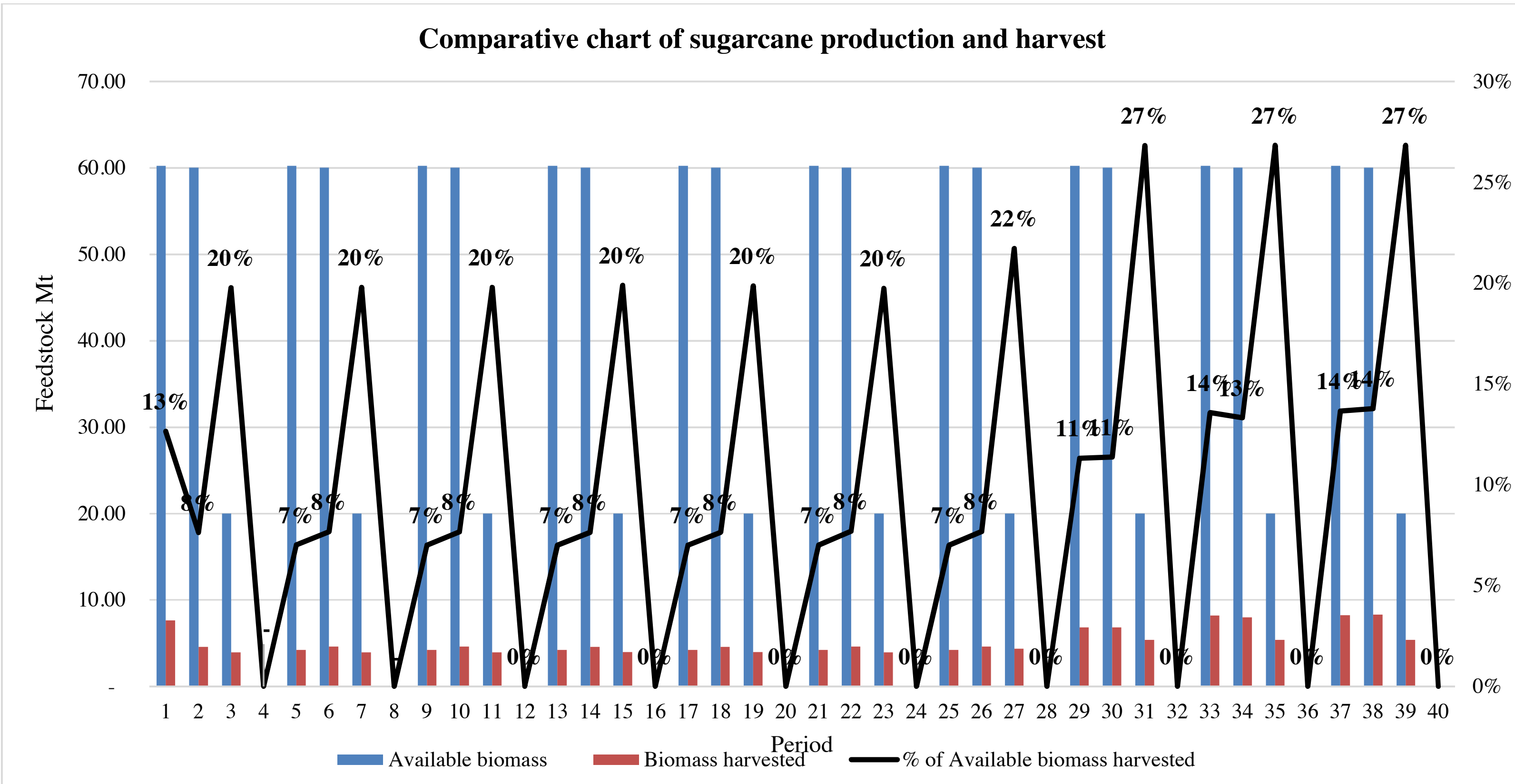
Period (Quarter)	Feedstock Harvest (t/quarter)		Feedstock Inventory (t/quarter)		Total Feed Processed (t/quarter)						Biofuel Produced (t/quarter)			BIOFUEL INVENTORY IN PLANT
					Q1		**Q2**		**Q3**		**Q1**	**Q2**	**Q3**	
	B1	**B2**	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**	**B1**	**B2**				
23	4,413,251	1,439,996	-	866,978	4,254,628	-	-	1,123,510	1,995	701,077	268,042	359,523	224,470	142,287
24	-	1,758,038	-	866,978	-	-	-	1,074,861	-	683,177	-	343,955	218,617	100,694
25	4,221,535	1,624,626	-	822,915	4,254,628	-	-	1,038,619	6,088	626,000	268,042	332,358	200,703	128,828
26	5,360,018	2,209,194	-	1,235,234	4,254,628	-	-	1,171,875	-	781,250	268,042	375,000	250,000	145,981
27	5,356,715	1,447,771	-	886,130	4,654,270	-	-	1,101,563	-	768,042	293,219	352,500	245,773	148,211
28	-	1,758,038	-	886,130	-	-	-	1,066,406	-	691,631	-	341,250	221,322	101,540
29	8,315,625	1,624,626	-	829,241	6,499,138	-	-	1,103,919	342,470	666,951	409,446	353,254	235,000	199,441
30	8,226,388	2,159,509	-	1,191,875	6,499,138	-	-	1,171,875	-	781,250	409,446	375,000	250,000	237,776
31	5,372,176	1,381,729	-	849,997	5,670,702	-	-	1,101,563	12,834	731,077	357,254	352,500	234,753	240,824
32	-	1,624,626	-	849,997	-	-	-	984,001	-	640,625	-	314,880	205,000	147,571
33	9,409,660	1,299,270	-	732,490	6,484,166	-	-	1,122,971	1,776,098	385,286	408,502	359,351	235,186	241,011
34	9,330,300	1,764,005	-	978,898	6,631,195	-	-	1,092,553	1,106,987	563,312	417,765	349,617	250,000	347,315
35	5,372,176	1,006,912	-	655,864	5,640,298	-	-	798,063	31,853	545,581	355,339	255,380	176,593	241,907
36	-	1,177,397	-	655,864	-	-	-	710,938	-	546,875	-	227,500	175,000	92,058
37	9,390,489	1,028,479	-	589,961	6,303,562	-	-	788,770	1,967,795	393,000	397,124	252,406	249,731	141,617
38	9,326,250	1,650,348	-	891,282	6,673,278	-	-	1,015,625	1,292,664	526,757	420,416	325,000	250,000	162,433
39	5,372,176	734,142	-	536,837	5,623,692	-	-	763,128	23,641	546,875	354,293	244,201	176,489	133,917
40	-	892,155	-	471,961	-	-	-	710,938	64,876	546,875	-	227,500	175,000	76,631

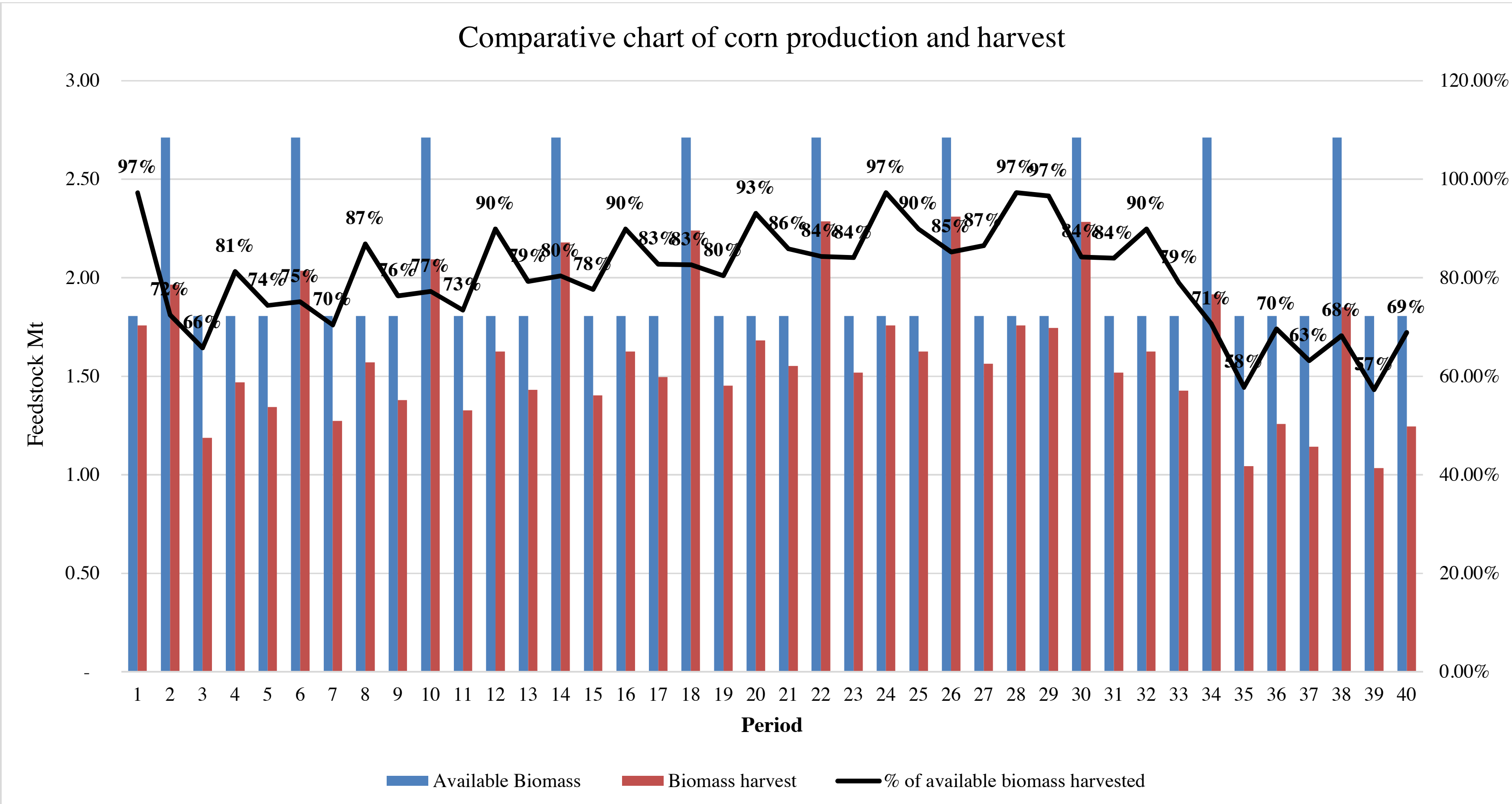
Continued

Period T	BIOFUEL DISTRIBUTED TO DC	BIOFUEL INVENTORY AT DC	BIOFUEL CONSUMED AT DC	GASOLINE DISTRIBUTED TO DC	GASOLINE INVENTORY AT DC	GASOLINE CONSUMED AT DC	BLEND PRODUCED	SALES	DEMAND	UNMNET DEMAND
1	778,214	47,694	667,041	1,322,321	205,488	1,232,930	1,899,971	1,899,971	1,901,876	1,905
2	792,676	164,170	656,451	1,207,724	201,581	1,209,487	1,865,937	1,865,937	1,865,937	-
3	751,154	252,134	675,690	2,395,526	206,826	1,240,959	1,916,648	1,916,648	1,916,648	-
4	510,134	51,000	713,998	1,373,289	217,854	1,307,124	2,021,121	2,021,121	2,021,121	-
5	679,195	48,869	684,167	30,559	208,084	1,248,504	1,932,671	1,932,671	1,932,671	-
6	790,047	197,739	672,625	2,357,841	203,918	1,223,510	1,896,135	1,896,135	1,896,135	-
7	773,527	271,748	692,399	121,604	209,240	1,255,440	1,947,840	1,947,840	1,947,840	-
8	541,213	52,273	731,821	1,327,460	220,443	1,322,659	2,054,480	2,054,480	2,054,480	-
9	695,906	50,074	701,037	1,258,683	210,491	1,262,948	1,963,985	1,963,985	1,963,985	-
10	807,488	185,579	689,205	2,385,062	206,273	1,237,636	1,926,841	1,926,841	1,926,841	-
11	790,923	266,104	709,530	123,110	211,672	1,270,030	1,979,560	1,979,560	1,979,560	-
12	558,601	53,579	750,099	1,343,193	223,053	1,338,316	2,088,415	2,088,415	2,088,415	-
13	713,036	51,309	718,331	2,459,398	212,916	1,277,496	1,995,826	1,995,826	1,995,826	-
14	837,593	177,579	706,201	63,787	208,644	1,251,864	1,958,065	1,958,065	1,958,065	-
15	811,432	263,164	727,093	1,287,073	214,121	1,284,726	2,011,818	2,011,818	2,011,818	-
16	561,531	54,917	768,843	1,359,049	225,682	1,354,094	2,122,937	2,122,937	2,122,937	-
17	730,594	52,576	736,058	2,487,573	215,358	1,292,147	2,028,205	2,028,205	2,028,205	-
18	856,378	164,705	723,623	64,487	211,032	1,266,191	1,989,815	1,989,815	1,989,815	-
19	829,205	263,632	745,098	2,508,612	216,588	1,299,527	2,044,625	2,044,625	2,044,625	-
20	579,872	56,290	788,066	168,321	228,332	1,369,992	2,158,058	2,158,058	2,158,058	-

Period T	BIOFUEL DISTRIBUTED TO DC	BIOFUEL INVENTORY AT DC	BIOFUEL CONSUMED AT DC	GASOLINE DISTRIBUTED TO DC	GASOLINE INVENTORY AT DC	GASOLINE CONSUMED AT DC	BLEND PRODUCED	SALES	DEMAND	UNMNET DEMAND
21	748,592	89,605	754,231	2,515,942	217,817	1,306,900	2,061,131	2,061,131	2,061,131	-
22	863,856	187,463	741,483	65,190	213,436	1,280,617	2,022,100	2,022,100	2,022,100	-
23	853,724	283,129	763,558	2,196,713	219,072	1,314,432	2,077,990	2,077,990	2,077,990	-
24	604,165	57,698	807,779	511,255	231,001	1,386,008	2,193,787	2,193,787	2,193,787	-
25	772,969	64,068	772,861	1,317,162	220,292	1,321,752	2,094,613	2,094,613	2,094,613	-
26	875,888	165,820	759,792	2,495,868	215,857	1,295,139	2,054,932	2,054,932	2,054,932	-
27	889,263	304,669	782,483	1,363,739	304,074	1,329,439	2,111,923	2,111,923	2,111,923	-
28	609,242	62,283	827,996	172,854	233,690	1,402,140	2,230,137	2,230,137	2,230,137	-
29	899,799	252,258	791,960	1,332,028	322,477	1,336,702	2,128,662	2,128,662	2,128,662	-
30	996,111	511,427	778,561	1,571,981	391,564	1,309,756	2,088,318	2,088,318	2,088,318	-
31	941,460	626,442	801,887	2,331,389	452,197	1,344,546	2,146,434	2,146,434	2,146,434	-
32	613,133	241,230	848,730	175,155	236,398	1,418,388	2,267,118	2,267,118	2,267,118	-
33	909,599	296,858	811,539	2,244,213	225,291	1,351,748	2,163,288	2,163,288	2,163,288	-
34	911,078	486,827	797,802	915,750	221,846	1,324,466	2,122,269	2,122,269	2,122,269	-
35	892,720	714,687	821,782	2,134,441	308,080	1,359,752	2,181,533	2,181,533	2,181,533	-
36	552,349	419,348	851,490	177,478	234,038	1,404,230	2,255,721	2,255,721	2,304,743	49,022
37	849,703	511,640	825,223	1,362,041	226,065	1,356,389	2,181,612	2,181,612	2,198,500	16,888
38	974,600	699,718	800,709	2,051,400	218,619	1,311,715	2,112,424	2,112,424	2,156,795	44,371
39	803,500	585,721	829,840	1,940,339	225,818	1,354,905	2,184,745	2,184,745	2,217,232	32,487
40	459,786	61,340	842,718	1,527,384	228,557	1,371,341	2,214,059	2,214,059	2,343,023	128,963

APPENDIX D - Comparative charts of biomass production and harvest




Comparative chart of corn production and harvest
Feedstock Mt
Period
Available Biomass
Biomass harvest
% of available biomass harvested
3.00
2.50
2.00
1.50
1.00
0.50
-
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
97%
72%
66%
81%
74%
75%
70%
87%
76%
77%
73%
90%
79%
80%
78%
90%
83%
83%
80%
93%
86%
84%
84%
97%
90%
85%
87%
97%
97%
84%
84%
90%
79%
71%
58%
70%
63%
68%
57%
69%

APPENDIX E- Detailed sugarcane production profile

Period	AC	AL	AP	AM	BA	CE	DF	GO	MA	MG
1	0	1535447	0	0	981169.4	38527.4	0	0	648389.4	0
2	0	1074813	0	0	793283.1	15410.96	0	0	446613.5	0
3	0	1074813	0	0	370498.9	4169.323	0	0	215411.7	0
4	0	0	0	0	0	0	0	0	0	0
5	0	1074813	0	0	495467.4	0	0	0	314086.3	0
6	0	1074813	0	0	746939.7	5496.181	0	0	443562.5	0
7	0	1074813	0	0	370498.9	0	0	0	215411.7	0
8	0	0	0	0	0	0	0	0	0	0
9	0	1074813	0	0	518042.1	0	0	0	313742.8	0
10	0	1074813	0	0	754975.4	7428.451	0	0	443393.1	0
11	0	1074813	0	0	370498.9	3859.61	0	0	215411.7	0
12	0	0	0	0	0	0	0	0	0	0
13	0	1074813	0	0	510786.1	0	0	0	313742.8	0
14	0	1074813	0	0	772654.9	15020.94	0	0	443393.1	0
15	0	1074813	0	0	370498.9	0	0	0	215411.7	0
16	0	0	0	0	0	0	0	0	0	0
17	0	1074813	0	0	500094.1	0	0	0	313742.8	0
18	0	1074813	0	0	767469.9	15995.19	0	0	443393.1	0
19	0	1074813	0	0	370498.9	0	0	0	215411.7	0
20	0	0	0	0	0	0	0	0	0	0
21	0	1074813	0	0	538488.1	0	0	0	313742.8	0
22	0	1074813	0	0	706477.4	13622.46	0	0	443393.1	0
23	0	1143239	0	0	370498.9	0	0	0	215411.7	0
24	0	0	0	0	0	0	0	0	0	0
25	0	1074813	0	0	538488.1	0	0	0	313742.8	0

Period	AC	AL	AP	AM	BA	CE	DF	GO	MA	MG
26	0	1074813	0	0	706477.4	13537.42	0	0	443393.1	0
27	0	2081740	0	0	370498.9	0	0	0	215411.7	0
28	0	0	0	0	0	0	0	0	0	0
29	0	2725923	0	0	769268.7	40816.47	0	0	516340	0
30	0	2725923	0	0	937258	12689.35	0	0	577611.7	0
31	0	2081740	0	0	370498.9	13560.29	0	0	215411.7	0
32	0	0	0	0	0	0	0	0	0	0
33	0	2725923	0	0	1115202	40816.47	0	0	648389.4	0
34	0	2725923	0	0	1111497	40680.87	0	0	646235.2	0
35	0	2081740	0	0	370498.9	13560.29	0	0	215411.7	0
36	0	0	0	0	0	0	0	0	0	0
37	0	2725923	0	0	1115202	40816.47	0	0	648389.4	0
38	0	2725923	0	0	1111497	40680.87	0	0	646235.2	0
39	0	2081740	0	0	370498.9	13560.29	0	0	215411.7	0
40	0	0	0	0	0	0	0	0	0	0

Continuation

Period	MS	PA	PB	PE	PI	RN	RO	RR	SE	TO
1	0	0	1649910	1352236	232930.3	328678	0	0	409387.2	0
2	0	0	874823.2	946565.5	157297.1	230074.6	0	0	223404.7	0
3	0	0	660288.5	1114312	84045.03	226904	0	0	222718.6	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	837216.7	946565.5	46460.1	230074.6	0	0	203806.2	0
6	0	0	874404.5	946565.5	115925.9	230074.6	0	0	235979.6	0
7	0	0	660288.5	1089476	84045.03	226904	0	0	222718.6	0
8	0	0	0	0	0	0	0	0	0	0
9	0	0	837216.7	946565.5	53356.93	230074.6	0	0	204732.4	0
10	0	0	874404.5	946565.5	109029	230074.6	0	0	236905.8	0
11	0	0	660288.5	1089476	84045.03	226904	0	0	222718.6	0
12	0	0	0	0	0	0	0	0	0	0
13	0	0	837216.7	946565.5	54241.02	230074.6	0	0	203806.2	0
14	0	0	854554	946565.5	108145	230074.6	0	0	236905.8	0
15	0	0	660288.5	1109327	84045.03	226904	0	0	222718.6	0
16	0	0	0	0	0	0	0	0	0	0
17	0	0	837216.7	946565.5	54241.02	230074.6	0	0	203806.2	0
18	0	0	874404.5	946565.5	110046.3	230074.6	0	0	238480.9	0
19	0	0	660288.5	1319305	82143.67	226904	0	0	221143.6	0
20	0	0	0	0	0	0	0	0	0	0
21	0	0	837216.7	946565.5	66523.24	230074.6	0	0	214357.3	0
22	0	0	876682.8	946565.5	97764.09	230074.6	0	0	227929.8	0
23	0	0	660288.5	1493621	82143.67	226904	0	0	221143.6	0
24	0	0	0	0	0	0	0	0	0	0
25	0	0	836464.2	946565.5	66780.7	230074.6	0	0	214605.8	0

Period	MS	PA	PB	PE	PI	RN	RO	RR	SE	TO
26	0	0	1285705	1280829	97506.63	230074.6	0	0	227681.3	0
27	0	0	660288.5	1497009	82143.67	226904	0	0	222718.6	0
28	0	0	0	0	0	0	0	0	0	0
29	0	0	1418229	1947475	252975.5	328678	0	0	315919.4	0
30	0	0	1248902	1947475	131932	328678	0	0	315919.4	0
31	0	0	660288.5	1497009	84045.03	226904	0	0	222718.6	0
32	0	0	0	0	0	0	0	0	0	0
33	0	0	1679818	1947475	252975.5	328678	0	0	670383.1	0
34	0	0	1609520	1947475	252135.1	328678	0	0	668155.9	0
35	0	0	660288.5	1497009	84045.03	226904	0	0	222718.6	0
36	0	0	0	0	0	0	0	0	0	0
37	0	0	1673441	1947475	252975.5	328678	0	0	657589.2	0
38	0	0	1605471	1947475	252135.1	328678	0	0	668155.9	0
39	0	0	660288.5	1497009	84045.03	226904	0	0	222718.6	0
40	0	0	0	0	0	0	0	0	0	0

APPENDIX F- Detailed corn production profile.

Period	AC	AL	AP	AM	BA	CE	DF	GO	MA	MG
1	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	0
2	0	0	0	0	648799.5	176744.2	87572.1	298740.6	304148.6	0
3	0	0	0	0	432533	117829.5	58381.4	65569.11	202765.7	0
4	0	0	779.52	0	432533	117829.5	58381.4	346256.1	202765.7	0
5	0	0	0	0	432533	117829.5	58381.4	25673.61	202765.7	0
6	0	0	0	0	648799.5	176744.2	87572.1	380281.4	304148.6	0
7	0	0	0	0	432533	117829.5	58381.4	30538.08	202765.7	0
8	0	0	779.52	0	432533	117829.5	58381.4	343910.9	202765.7	0
9	0	0	0	0	432533	117829.5	58381.4	110645.1	202765.7	0
10	0	0	0	0	648799.5	176744.2	87572.1	391121.4	304148.6	0
11	0	0	0	0	432533	117829.5	58381.4	117264.4	202765.7	0
12	0	0	779.52	0	432533	117829.5	58381.4	423096.7	202765.7	0
13	0	0	0	0	432533	117829.5	58381.4	147309.4	202765.7	0
14	0	0	0	0	648799.5	176744.2	87572.1	417800.4	304148.6	0
15	0	0	0	0	432533	117829.5	58381.4	195284.2	202765.7	0
16	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	70971.37
17	0	0	0	0	432533	117829.5	58381.4	192956.1	202765.7	0
18	0	0	0	0	648799.5	176744.2	87572.1	443966.1	304148.6	0
19	0	0	0	0	432533	117829.5	58381.4	239533.8	202765.7	0
20	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	93053.86
21	0	0	0	0	432533	117829.5	58381.4	424163.6	202765.7	0
22	0	0	0	0	648799.5	176744.2	87572.1	360045.9	304148.6	0
23	0	0	779.52	0	432533	117829.5	58381.4	239533.8	202765.7	0
24	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	93053.86
25	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	0

Period	AC	AL	AP	AM	BA	CE	DF	GO	MA	MG
26	0	0	0	0	648799.5	176744.2	87572.1	409670.1	304148.6	0
27	0	0	779.52	0	432533	117829.5	58381.4	247308.5	202765.7	0
28	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	93053.86
29	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	0
30	0	0	0	0	648799.5	176744.2	87572.1	359984.8	304148.6	0
31	0	0	0	0	432533	117829.5	58381.4	182045.7	202765.7	0
32	0	0	779.52	0	432533	117829.5	58381.4	424163.6	202765.7	0
33	0	0	0	0	432533	117829.5	58381.4	99587.5	202765.7	0
34	0	0	0	0	648799.5	176744.2	87572.1	0	304148.6	0
35	0	0	0	0	404599	117829.5	0	0	202765.7	0
36	0	0	0	0	432533	117829.5	36095.6	0	202765.7	0
37	0	0	0	0	432533	117829.5	0	0	202765.7	0
38	0	0	0	0	648799.5	176744.2	6958.307	0	304148.6	0
39	0	0	0	0	339291.4	117829.5	0	0	604.1792	0
40	0	0	0	0	432533	98608.06	0	0	109375	0

Continuation

Period	MS	PA	PB	PE	PI	RN	RO	RR	SE	TO
1	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
2	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
3	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
4	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
5	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
6	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
7	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
8	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
9	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
10	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
11	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
12	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
13	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
14	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
15	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
16	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
17	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
18	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
19	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
20	38310	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
21	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
22	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
23	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
24	40357.93	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
25	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73

Period	MS	PA	PB	PE	PI	RN	RO	RR	SE	TO
26	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
27	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
28	40357.93	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
29	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
30	0	68562.4	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
31	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
32	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
33	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
34	0	33043.34	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
35	0	0	8257.956	31682.56	236874.8	4902.898	0	0	0	0
36	0	45708.26	8257.956	31682.56	236874.8	4902.898	0	0	0	60746.73
37	0	0	8257.956	25314.93	236874.8	4902.898	0	0	0	0
38	0	0	12386.93	47523.84	355312.3	7354.347	0	0	0	91120.09
39	0	0	8257.956	27451.6	236874.8	3832.763	0	0	0	0
40	0	0	8257.956	31682.56	206795	4902.898	0	0	0	0