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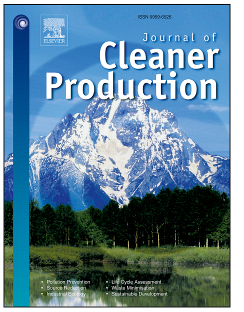

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Bio-Supply Chain Network Design to Tackle Ethanol Deficiency in India: A Mathematical framework

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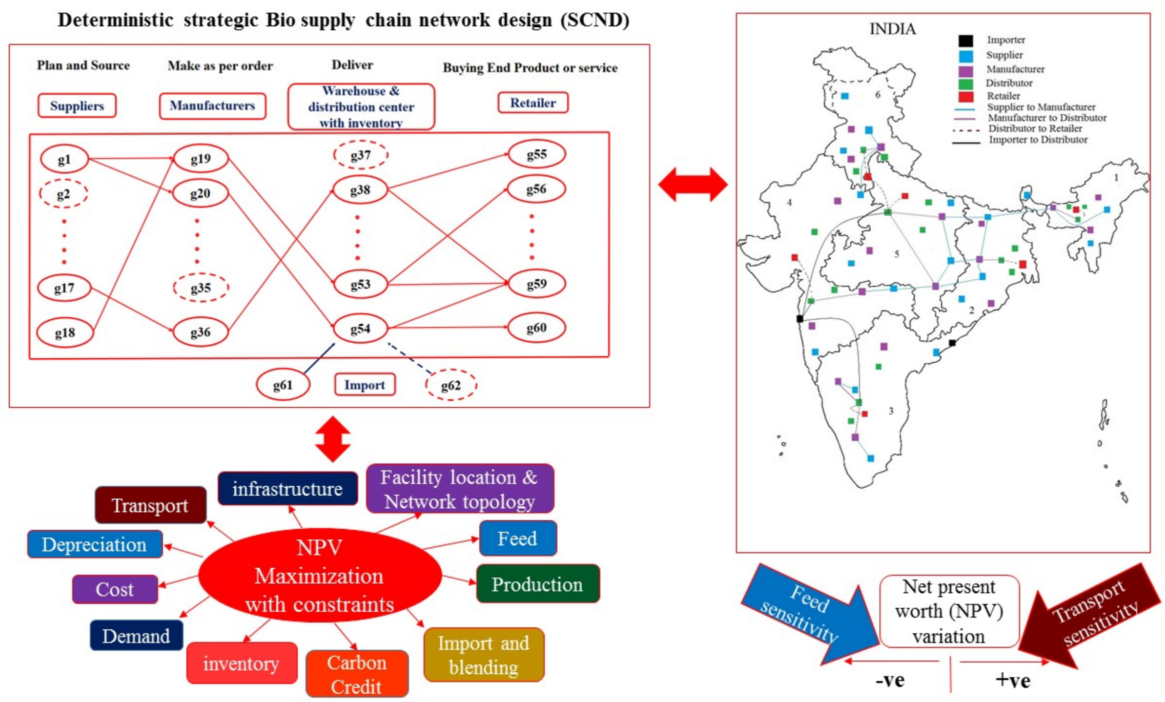
Deterministic strategic Bio supply chain network design (SCND)
Plan and Source
Make as per order
Deliver
Buying End Product or service
Suppliers
Manufacturers
Warehouse & distribution center with inventory
Retailer
g1
g2
g17
g18
g19
g20
g35
g36
g37
g38
g53
g54
g55
g56
g59
g60
g61
Import
g62
Transport
infrastructure
Facility location & Network topology
Depreciation
Feed
NPV Maximization with constraints
Cost
Production
Demand
inventory
Carbon Credit
Import and blending
INDIA
Importer
Supplier
Manufacturer
Distributor
Retailer
Supplier to Manufacturer
Manufacturer to Distributor
Distributor to Retailer
Importer to Distributor
Feed sensitivity
Net present worth (NPV) variation
Transport sensitivity
-ve
+ve

Abstract

To deal with the rising demand of fossil fuels and their associated untoward environmental and economic effects, the feasibility of Indian government's green move towards blending of 20% fuel grade ethanol with gasoline has been studied by performing techno-economic-environmental analysis of second generation lignocellulose biomass as feedstock. An optimized supply chain network (SCN) has been designed with four layers of structure starting from raw material suppliers to the retailers through the layers of the manufacturers and the distributors aiming at the net present value (NPV) maximization. The cost calculation includes operating expenditure (OPEX) and capital expenditure (CAPEX) components involving transport, storage, production and import decisions as linear variables and decisions on connections between two nodes between two consecutive layers as binary variables. The distribution layer of the mixed integer linear programming (MILP model has been uniquely designed for the imported ethanol to serve the twin purposes of meeting the unmet demand as well as enhancing the bio-ethanol product quality in term of research octane number. The revenue generation is calculated not only from selling the final product but also from the carbon credits calculated using greenhouse gas emission (GHGe) during project life cycle assessment. Further, sensitivity analysis has been performed to show the effect of various parameters such as modes of transport, transport distance limitation on feedstock and product, number of zones, international fuel price fluctuations, feedstock availability on NPV. With ~80% increase in demand over the 9-year planning horizon, a dynamically changing supply chain (SC) structure shows a ~36% increase in the newly added locations. Feed availability, critical for Indian scenario, to the tune of at least 40% of the capacity is needed to meet the projected demands.

Keywords: Supply Chain Network Design; MILP; Bioethanol; Blending; Lignocellulose biomass; NPV.

1. Introduction

The reserve of fossil fuels that are being used as energy resource is depleting day by day (Razm et al., 2019). The rising pace of development across the globe has led to a great demand-supply imbalance for these conventional fuels, causing unexpected cost escalation and economic inflation (Dovì et al., 2009). Apart from this, they have vital role in environmental pollution (Liu et al., 2018). Thus, a need is felt to migrate from non-renewable to renewable resources of energy, providing immense opportunity to various untapped renewable resources namely, solar, wind, hydro, geothermal, tidal and bio energy (Sequeira and Santos, 2018). Fig 1 (Govt of India Minsitry of Power, 2018; Ministry of Natural Resources and Environment, 2018) shows the current usage of different sources of energy in India.

--- Figure 1 about here ---

Amidst these alternatives, bioenergy, more precisely bioethanol, generated from 2nd generation biomass (~ 13%, Fig 1b) is one of the sources of carbon neutral renewable energy that is gaining popularity in India. This is because the major part of economy and society in India depends on forest and agriculture and 70% of the its population represents rural India (Yong et al., 2016; Natarajan et al., 2015). As per the government regulation, it is mandatory to blend fuel grade ethanol with gasoline to reduce the burden of crude oil import and this blending percentage is increasing over years (Tables 1 and 2) (Ahmad, 2018; Aradhey, 2017). Moreover, this sector can provide jobs to local people and help boost the national gross domestic product. The low pollution greenhouse gas emission (GHGe) can help in getting revenue in the form of carbon credits for biofuels as per the Kyoto protocol (Grubb et al, 1997). This particular aspect of green energy can provide an edge over the depleting fossil energy despite the metric of energy released per unit mass is less for bioethanol compared to the fossil fuel (Krajnc, 2015). A thorough analysis across the entire supply chain network (SCN) (Fig. 2) (Reid and Sanders, 2015; Simchi-Levi et al., 2015) during the planning stage will, therefore, be the key behind the success of such a potential initiative in India.

--- Figure 2 about here ---

Several works have been reported in the area of biofuel supply chains and its network design covering the basic taxonomy, prevailing and best practices, available technologies and their associated pros and cons with future directions (Koberg and Longoni, 2019). Among few recent specific works, Zamboni et al. (2009a, 2009b) presented a mixed integer linear programming (MILP) strategic design model for biofuel supply network for Italy that reduces the total daily cost and GHGe following single and multi-objective approaches. In another work (Giarola et al., 2011), bi-objective criteria of maximization of net present value (NPV) and minimization of GHGe for the north Italian geography have been studied for a corn grain and stover based bioethanol supply chain through the combination of first and second generation technologies. Akgul et al. (2010) introduced 4 and 8 neighborhoods (4N & 8N) based rectangular supply chain (SC) design technique for bioethanol production and its distribution for corn in north Italy to show a possible reduction in the problem size (167653 constraints to 1520 and

1920 by 4N and 8N respectively) by a factor of 100 and thereby achieving savings in model execution time (reduction from 285 seconds to 12 seconds) compared to earlier results (Zamboni et al., 2009a). Carvajal et al. (2019) proposed a sugarcane SC planning model for Columbia integrating strategic (long) and tactical (mid) decision to maximize cane yield leading to NPV maximization subject to constraints on sowing, growing and harvesting.

SCN planning for bioethanol has been developed by Duarte et al. (2016) for Colombian geography considering 2nd generation biomass feed from coffee cut stem. The MILP model addresses economics (profit) and environmental impact taking care of facility locations, unfulfilled penalty cost, CO_2 price sensitivity in a multi period fashion. Calderón et al. (2017) performed a detailed cost analysis while designing a bio-synthetic natural gas supply chain as an alternative to fossil fuels and power cogeneration in United Kingdom with the aim of maximizing NPV after meeting GHGe targets. This work considers the presence of multiple feed stocks across a diverse geography and follows the government's tariff plan, renewable obligation certificate and renewable heat incentive rules. Targeting Oklahoma State, Haque and Epplin (2012) performed the breakeven analysis for ethanol production from switch grass biomass by considering land use service, feedstock production, harvest, harvest machine investment, storage, transportation, location, size and investment of bio-refinery. The bio-refinery supply chain of British Columbia using forest and wood resources has been presented by Cambero et al. (2015). The MILP model determines facility location, type and quantum of technology, biofuel and bioenergy distribution to increase NPV while producing heat, electricity, pellets and pyrolysis oil. They also performed the sensitivity analysis of raw material availability, demand and price fluctuation on NPV. In continuation to this work, Cambero et al. (2016) incorporated several other objectives such as GHGe saving and objective of job creations and thereby maximizing social benefits (Cambero and Sowlati, 2016) to obtain the trade-off solutions among the objectives set.

Liu et al. (2014) performed multi-objective optimization (maximization of profit, minimization of GHGe and Fossil energy input) considering the geography of China, where three different biofuels (bio-ethanol, bio-methanol and bio-diesel) are manufactured using four different feeds. Multi-objective optimization study for designing sustainable bioethanol SC using multiple agricultural residue feed from coffee crop has also been proposed for Colombian geography (Chávez et al., 2018) considering seasonality. Here, using three objectives (maximize NPV and job creation, minimize water-air pollutants), four layered SC has been designed in multi-period fashion solving strategic and tactical decision on dynamic capacity planning integrated with inventory decisions. Similar attempt for economic, environment and social sustainability in Bio SC with tri-objective MILP model have been made (Santibañez-Aguilar et al. 2014), where multiple feed stocks as per seasonality, diverse production technologies, economy of scale, facility location, transportation modes, multiple periods are considered to generate bioethanol and biodiesel in Mexico. Further, one can refer to several review papers (Eskandarpour et al., 2015; Budzianowski and Postawa, 2016; Zandi et al., 2018), where overview of past, present and future methodologies and implementation of bio SC have been explained along with the classical and heuristic techniques to find solutions.

In this work, authors have proposed a planning model working on the futuristic demand for fuel grade bio-ethanol to be blended with gasoline over a 9-year time horizon (2018 - 2026). Considering storage, import, transport, production as continuous variables and connection between the nodes between SC layers as binary variables, the MILP model can show the feasibility of meeting India's future demand for ethanol through biological route (2^{nd} generation biomass) in a four layer (supplier, manufacturer, warehouse, retailers) SC network. Such kind of techno-economic-environmental feasibility study for country wide supply chain does not exist in the literature for Indian scenario. Novelty in terms of handling different scenarios for India appears while considering (i) import of ethanol from other nations in case of production deficit to meet demand and utilizing the same as quality enhancing agent in terms of research octane number (RON) of the final blended product, (ii) greenhouse gas emissions (GHGe) calculations to earn carbon credits to create extra source of income in NPV calculation, and (iii) making use of multiple feed stock for bio-ethanol to be processed via multiple technologies at single manufacturing location to deal with feed scarcity. Impact of varying parameters such as modes of transport, limitation on transported distance for feed and products, international fuel price fluctuations, feed stock availability on NPV has been shown and discussed. The rest of the paper is organized as follows. Section 2 explains the problem statement followed by the model equations and their explanations in Section 3. Section 4 elaborates on results and discussions, whereas the conclusions and the directions for future work are presented in section 5.

2. Problem Formulation

The proposed SCN model has been developed considering four SC layers namely, suppliers, manufacturers, distributors and retailers (Fig 3). The target of SCN design is to find such a network that will reduce the overall cost while maximizing NPV of the project satisfying all the given supplier, manufacturing, storage, transport and import constraints. Food versus fuel issue has been tackled by selecting only the second generation biomass feed, known as lignocellulose biomass. These feed stocks cannot be consumed by humans and have the government approval to be considered as biomass feed (Table 3). Considering all types of raw material might not be available all over the country in required amount, the Indian geography has been divided into six major zones, representing a decentralized strategy for this study (Fig 4a and Table 4). Within each zone, 3 suppliers, 3 manufacturers, 3 distributors and 1 demand center locations have been considered (Tables 4 and 5). Overall, there are 18 suppliers (g_1 - g_{18}) with good farming land and water resources, 18 manufacturers (g_{19} - g_{36}) closer to supplier locations to facilitate quicker supply of feed stocks, 18 distributors with inventory (g_{39} - g_{54}) near to retailer locations and 6 retailers (g_{55} - g_{60}) having high demand and consumption of gasoline as depicted in Fig. 3. Also, two locations are identified as import facility locations (g_{61} and g_{62}) with good port facilities (Table 5).

Following assumptions are followed while developing the model equations:

1. Transfer of material occurs sequentially (supplier – manufacturer – distributor – customer). There is no backflow and jump of material in the SC.
2. The model involves binary numbers to designate whether a location exits in a SC layer. There is connection only between two consecutive layers.
3. The model is deterministic in nature.

4. Transfer of material flow is not restricted by zone boundaries e.g. supplier of one zone can transfer to manufacturer of any zone, if the biomass processing technology is available at that site; the same logic is valid for manufacturing and distributor layers.
5. Locations in the same layer within or across zones do not transfer material among them.
6. Money flows in the reverse direction i.e. from customer to supplier.
7. Pretreatment of raw material is done at the manufacturing site.
8. Four major biomass materials and their corresponding technologies of conversion have been chosen based on Indian conditions.
9. In case of shortage of supply of product at retailer, the demand is satisfied via imports, which are blended at distributor locations having inventory.
10. There exit rail and road connections within locations in the SC.

The nomeclautre used in the model in the form of sets, subsets, indices, parameters, and variables is presented in Tables 6 – 10.

--- Figure 3 about here ---

The model covers the following decisions:

- SCN structure
- Facility locations
- Supply of raw materials
- Production at manufacturing site
- Imports from overseas
- Distributors with inventory
- Meeting product demand as per market
- Transport for connectivity
- Blending import with indigenous product to maintain RON quality
- Pollution control and carbon credits
- Cost consideration for various SCN components
- Non negative physical variables and binary decisions

--- Figure 4a about here ---

--- Figure 4b about here ---

2.1. Objective function

Net present value (NPV) calculates the project economy, taking into consideration the time value of money and taxes. Depreciation is an integral part of NPV calculation as the physical value of assets decreases with time. The sinking fund method has been used to calculate the deprecation, which gives uniform annual payments made at the end of each year. The salvage value obtained at the end of time period is assumed as 20% of the cost invested (Peters et al., 1968). The revenue is obtained by selling the ethanol to the retailers and earning carbon credits, whereas the cost incurred has been assigned to major factors of operating expenditure (OPEX) namely transportation, inventory, production, imports and capital expenditure (CAPEX) namely infrastructure. The NPV value zero and above is considered as a project worth investing (Peters et al., 1968).

Max NPV

$$NPV = \sum_t \frac{1}{(1+alpha)^{N-1}} \left(\left(Earning_t - Opex_t - Depr \right) \times (1 - phi) + Depr \right) - \sum_t \frac{1}{(1+alpha)^{N-1}} \left(Capex_t \right) \quad (1)$$

$$Earning_t = \sum_{p,ru} Dem_{p,ru,t} \times SP_{p,t} + GHGeRevenue_t \quad (2)$$

$$Opex_t = TranC_t + InvtCdu_t + PrdnC_t + ImpC_t \quad (3)$$

$$Cpex_t = InfraC_t \quad (4)$$

$$Depr = \sum_t \frac{i}{((1+i)^{N} - 1)} \left(InfraC_t - 0.2 \times InfraC_t \right) \quad (5)$$

2.2. Network Topology Count

Though the SCN explained in Fig 3 has many locations to be considered for each SC layer, all of them might not be present in the optimal configuration of the SCN based on NPV maximization. Binary variables are used to show the presence / absence (1 / 0, respectively) of a location (Table 9) in a SC network. Unnecessary choice of node incurs cost whereas the choice of no nodes leads to less revenue and thereby less NPV. NPV maximization objective ensures optimum number of nodes in each layer. The number of nodes at every layer is chosen obeying the bounds on the maximum number of nodes allowed for that layer. Eqs 6-10 calculate the total number of nodes in each layer at a certain time period.

$$nsu_{su,t} = \sum_{su} Ysu_{su,t} \quad , \quad \forall t, su \in g \quad (6)$$

$$nmu_{mu,t} = \sum_{mu} Ymu_{mu,t} \quad , \forall t, mu \in g \quad (7)$$

$$nim_{im,t} = \sum_{im} Yim_{im,t} \quad , \quad \forall t, im \in g \quad (8)$$

$$ndu_{du,t} = \sum_{du} Ydu_{du,t} \quad , \quad \forall t, du \in g \quad (9)$$

$$nru_{ru,t} = \sum_{ru} Yru_{ru,t} \quad , \quad \forall t, ru \in g \quad (10)$$

2.3. SCN material flow constraints

This section covers the material flow within the SCN with the aim of fulfilling the demand at retailers. As the information flow in a SCN happens in the retailer to supplier direction, material flow equations are written for a layer to fulfil the demand coming from the layer next to it.

2.3.1. Feed constraints

In India, based on seasonality, the crops can be categorized as Kharif, Rabi, Zaid and Perennial. Kharif crops are sown at the start of monsoon (~June) and harvested after maturation

(~October-November). Example is Feed1 (Sugarcane Bagasse) and Feed 3 (Corn Stover). Rabi crops are sown after the monsoon rains are over. At the start of winter season, seeds are sown and harvested after maturation in Spring season (~March-April). Zaid crops are sown in between Rabi and Kharif crops. Perennial crops are those which do not depend on any season. Example is Feed 2 (Bamboo) and Feed 4 (Woody plants). Thus, the crops are grown yearly in cyclic manner, which provides continuous biomass feed supply throughout the year (case 1, section 4.1). Based on this, four types of feed stocks are considered for this study.

Biomass feed available at supplier $Feed_{f,su,t}$ is transported to many other locations in the next manufacturer layer using transport medium l at time t (Eq11).

$$Feed_{f,su,t} = \sum_{mu} Qsumul_{f,su,mu,l,t} \quad , \forall f,\ \forall su,\ \forall l,\ \forall t,\ mu \in g \tag{11}$$

Feed stock availability at a supplier location has limitation on maximum amount. However, at the same time, there must be minimum quantity available to enable the technology to be economically viable. Following constraints (Eq 12 and 13) also ensure that the above is true only for the existing supplier nodes.

$$Feed_{f,su,t} \le FeedMax_{f,su,t} \times Ysu_{su,t}\ ,\ \forall f,\ \forall su,\ \forall t \tag{12}$$
$$FeedMin_{f,su,t} \times Ysu_{su,t} \le Feed_{f,su,t}\ ,\ \forall f,\ \forall su,\ \forall t \tag{13}$$

Quantity of feed transported from supplier to manufacturer $Qsumul_{f,su,mu,l,t}$ has limitation based on upper and lower bounds that can be supplied at a time period t by the available transport medium l (Eq 14 and 15). Binary variables ensure the connection between locations of supplier and manufacturer layers.

$$Qsumul_{f,su,mu,l,t} \le QsumulMax_{f,su,mu,l,t} \times Ymu_t, \forall su\_f_{su,f},\ \forall mu,\ \forall l,\ \forall t \tag{14}$$
$$QsumulMin_{f,su,mu,l,t} \times Ysu_{su,t} \le Qsumul_{f,su,mu,l,t}\ , \forall f,\ \forall su,\ \forall mu,\ \forall l,\ \forall t \tag{15}$$

2.3.2 Production constraints

Feed, $Qsumul_{f,su,mu,l,t}$ from various supplier facilities is transported into manufacturing locations, where it is converted into bioethanol (Eq 16). As mentioned earlier, each feed has separate technology that converts raw material into product $Pmutech_{p,mu,tech,t}$ based on the conversion factor (Eq 17). At the same time, the manufacturing site has production limitation of final product $Pmu_{p,mu,t}$ (Eq 18 and 19). Binary variables are used to impose such constraints.

$$\sum_{su} Qsumul_{f,su,mu,l,t} \times conv_{f,tech,p} = Pmutech_{p,mu,tech,t}, \forall mu, \forall tech, \forall p, \forall l, \forall t,\ \forall su\_f_{su,f}, su \in g \tag{16}$$

$$\sum_{tech} Pmutech_{p,mu,tech,t} = Pmu_{p,mu,t}\ , \ \forall p, \forall mu, \forall t, tech \in Tech \tag{17}$$

$$Pmu_{p,mu,t} \le PmuMax_{p,mu,t} \times Ymu_{mu,t}\ , \forall p,\ \forall mu,\ \forall t \tag{18}$$
$$PmuMin_{p,mu,t} \times Ymu_{mu,t} \le Pmu_{p,mu,t}\ , \forall p,\ \forall mu,\ \forall t \tag{19}$$

The product manufactured at one location can be transported to many locations in the next distribution layer using transport mode l (Eq 20). But the limitation on quantity of product transferred between these two layers $Qmudul_{p,mu,du,l,t}$ based on the bounds on the transferable amount is expressed by Eqs 21 and 22. These constraints make $Qmudul_{p,mu,du,l,t}$ nonzero in case a connection exists between two locations, otherwise zero.

$$Pmu_{p,mu,t} = \sum_{du} Qmudul_{p,mu,du,l,t} \quad , \forall p,\ \forall mu,\ \forall l,\ \forall t,\ du \in g \tag{20}$$
$$Qmudul_{p,mu,du,l,t} \leq QmudulMax_{p,mu,du,l,t} \times Ydu_{du,t} \quad , \forall p,\ \forall mu,\ \forall du,\ \forall l,\ \forall t \tag{21}$$
$$QmudulMin_{p,mu,du,l,t} \times Ymu_{mu,t} \leq Qmudul_{p,mu,du,l,t} \quad , \forall p,\ \forall mu,\ \forall du,\ \forall l,\ \forall t \tag{22}$$

2.3.3. Import constraints

In case of higher demands, when indigenous production is unable to meet the same, ethanol is imported from overseas to import facility locations (g_{61} and g_{62}, Table 5). Products from import facility locations can be transported to various distributor locations (Eq 23). Imports are also necessary to maintain RON of the final product. Quantity of Import, $import_{p,im,t}$ from overseas has limitation based on the storage capacity of the respective locations (Eqs 24 and 25). The quantity of product transferred $Qimdul_{p,im,du,l,t}$ from import facility to distributor facility has limitation based on the bounds on the amount transferable using transport medium, provided a connection is necessary (Eqs 26 and 27).

$$import_{p,im,t} = \sum_{du} Qimdul_{p,im,du,l,t} \quad , \quad \forall p, \forall im, \forall l, \forall t,\ du \in g \tag{23}$$
$$import_{p,im,t} \leq importMax_{p,im,t} \times Yim_{im,t} \quad , \forall p,\ \forall im,\ \forall t \tag{24}$$
$$importMin_{p,im,t} \times Yim_{im,t} \leq import_{p,im,t} \quad , \forall p,\ \forall im,\ \forall t \tag{25}$$

$$Qimdul_{p,im,du,l,t} \leq QimdulMax_{p,im,du,l,t} \times Ydu_{du,t} \quad , \forall p,\ \forall im,\ \forall du,\ \forall l,\ \forall t \tag{26}$$
$$QimdulMin_{p,im,du,l,t} \times Yim_{im,t} \leq Qimdul_{p,im,du,l,t} \quad , \forall p,\ \forall im,\ \forall du,\ \forall l,\ \forall t \tag{27}$$

2.3.4. Inventory constraints

The next layer is of distributors, where product is received not only from the previous manufacturing layer but also from the import locations and is forwarded from that distributor location to multiple locations in the next retailer layer. So the inventory at current time period $invtdu_{p,du,t}$ is sum of inventory at the previous time period $invtdu_{p,du,t-1}$ plus the quantity received from manufacturing $Qmudul_{p,mu,du,l,t}$ and import $Qimdul_{p,im,du,l,t}$, minus the quantity delivered to the retailer layer $Qdurul_{p,du,ru,l,t}$ (Eq 28) at the current time period. Moreover, while transferring material to the next layer, sufficient quantity of product is stored at distributors as inventory safety stock for future need. In addition, it is checked whether warehouse inventory capacity (Eq 29 and 30) and quantity transferred (Eq 31 and 32) from distributor to retailer are within the given bounds and the existence of facilities at these two locations is necessary or not.

$$invtdu_{p,du,t} = invtdu_{p,du,t-1} + \sum_{mu} Qmudul_{p,mu,du,l,t} + \sum_{im} Qimdul_{p,im,du,l,t} - \sum_{ru} Qdurul_{p,du,ru,l,t} \quad , \forall p,\ \forall du, \forall t, \forall l, \forall t,\ mu \in g,\ ru \in g \tag{28}$$

$$invtdu_{p,du,t} \leq invtduMax_{p,du,t} \times Ydu_{du,t}, \quad \forall p,\ \forall du,\ \forall l,\ \forall t \tag{29}$$
$$invtduMin_{p,du,t} \times Ydu_{du,t} \leq invtdu_{p,du,t}, \quad \forall p,\ \forall du,\ \forall l,\ \forall t \tag{30}$$

$$Qdurul_{p,du,ru,l,t} \leq QdurulMax_{p,du,ru,l,t} \times Yru_{ru,t} \quad , \forall p,\ \forall du,\ \forall ru,\ \forall l,\ \forall t \tag{31}$$

$QdurulMin_{p,du,ru,l,t} \times Ydu_{du,t} \leq Qdurul_{p,du,ru,l,t} \quad , \forall p,\ \forall du,\ \forall ru,\ \forall l,\ \forall t$ (32)

2.3.5. Blending constraints

The quality of ethanol imported $import_{p,im,t}$ is of higher RON as compared to that of indigenously manufactured products in the SC. So there is need to blend the imported ethanol with the indigenous product to obtain the final product of desired RON ensuring consistent product quality (assuming linear mixing rule Eq 33).

$\sum_{im} import_{p,im,t} \times$ imported ethanol RON + $\sum_{du} invtdu_{p,du,t} \times$ indigenous ethanol RON = desired ethanol RON $\times$ ($\sum_{im} import_{p,im,t}$+$\sum_{du} invtdu_{p,du,t}$), $\forall p, \forall t,\ im \in g,\ du \in g$ (33)

2.3.6. Demand constraints

Finally, the product from various warehouses should reach the retailer locations to satisfy the product demand. The sum of all the product transferred to the retailer location must be greater than or equal to the demand at that location at the same time period (Eq 34). If the supply becomes more than demand, excess product is stored in the inventory layer to get carried over to the next time period.

$\sum_{du} Qdurul_{p,du,ru,l,t} \geq Dem_{p,ru,t} \quad , \quad \forall p,\ \forall ru,\ \forall l,\ \forall t, du \in g$ (34)

2.4. Pollution constraints and carbon credits

GHGe is an indicator for pollution caused by any project in terms of equivalent mass of CO_2 (tons of CO_2e). GHGe is produced throughout the life cycle of project. This model includes following four major factors for GHGe as per SC life cycle assessment (Fig 5).

--- Figure 5 about here ---

- Biomass cultivation.
- Biofuel product manufacturing.
- Biofuel storage at distributor locations.
- Biomass and biofuel transportation from one layer of SC to another.

As the 2nd generation lignocellulose biomass has been used as feed, the average values of emission factor at biomass cultivation stage are similar to the order of lignocellulose materials. In general, $GHGe_{bc}$ is defined as

$GHGe_{bc} = \sum_{f,su,t} fbc_{f,t} \times Feed_{f,su,t}$ (35)

Based on the bio-product, the manufacturing unit will have its own emission factor. Here single product ethanol is made with four different types of feed. These feed types use generally same techniques of hydrolysis and fermentation that have similar kind of emission factors on an average and can be calculated as

$$GHGe_p = \sum_{p,mu,t} fp_{p,t} \times Pmu_{p,mu,t} \quad (36)$$

While keeping warehouse inventory, there is consumption of utilities in the form of energy, water etc. to maintain the inventory which contributes to GHGe as

$$GHGe_{du} = \sum_{p,du,t} fdu_{p,t} \times invtdu_{p,du,t} \quad (37)$$

GHGe is also produced through transportation modes (Eq 38). Here, two types of transportation between different layers contribute to GHGe through different emission factors.

$$GHGe_{trans} = \sum_{f,su,mu,l,t}(fsml_{f,l} \times dsumu_{su,mu} \times Qsumul_{f,su,mu,l,t}) + \sum_{p,mu,du,l,t}(fmdl_{p,l} \times dmudu_{mu,du} \times Qmudul_{p,mu,du,l,t}) + \sum_{p,im,du,l,t}(fimdl_{p,l} \times dimdu_{im,du} \times Qimdul_{p,im,du,l,t}) + \sum_{p,du,ru,l,t}(fdrl_{p,l} \times dduru_{du,ru} \times Qdurul_{p,du,ru,l,t}) \quad (38)$$

The overall GHGe (Eq 39), thus, can be obtained by adding all the GHGe components mentioned in the eqs 35 – 38.

$$GHGe_t = \sum_{f,su,t} fbc_f \times Feed_{f,su,t} + \sum_{p,mu,t} fp_p \times Pmu_{p,mu,t} + \sum_{p,du,t} fdu_p \times invtdu_{p,du,t} + \sum_{f,su,mu,l,t}(fsml_{f,l} \times dsumu_{su,mu} \times Qsumul_{f,su,mu,l,t}) + \sum_{p,mu,du,l,t}(fmdl_{p,l} \times dmudu_{mu,du} \times Qmudul_{p,mu,du,l,t}) + \sum_{p,im,du,l,t}(fimdl_{p,l} \times dimdu_{im,du} \times Qimdul_{p,im,du,l,t}) + \sum_{p,du,ru,l,t}(fdrl_{p,l} \times dduru_{du,ru} \times Qdurul_{p,du,ru,l,t}) \quad (39)$$

Eq. 39 calculates the GHGe for the ethanol project to meet the blending target demand. If the same amount of blending quantity of ethanol is replaced via gasoline fuel and its corresponding GHGe is calculated (Eq. 40), then Eq. 41 can help in determining the GHGe savings, which can be multiplied by the carbon credit rate to earn revenue (Eq. 42).

$$GHGeFo_t = GasoCarbon \times GasoED \times \sum_{p,ru} Dem_{p,ru,t} \quad (40)$$
$$GHGeSaving_t = GHGeFo_t - GHGe_t \quad (41)$$
$$GHGeRevenue_t = GHGeSaving_t \times CCval_t \quad (42)$$

2.5. Non-negative constraints

Feed supply, product manufactured and inventory are decision variables that cannot be negative (Eq 43, 44, 45 respectively).

$$Feed_{f,su,t} \geq 0 \ , \forall t, f \in F, su \in g \quad (43)$$
$$Pmu_{p,mu,t} \geq 0 \ , \forall t, p \in P, mu \in g \quad (44)$$
$$invtdu_{p,du,t} \geq 0 \ , \forall t, p \in P, du \in g \quad (45)$$

2.6. Costing

As shown in Eq 3 and 4, the NPV involves transportation, inventory, production and imports (OPEX) and infrastructure cost (CAPEX). Total cost is summation of these two components (Eq 46).

$$TotalCosting = Opex_t + Capex_t \quad (46)$$

Each cost component is given further in more details.

2.6.1. Transportation cost

Transportation cost includes the fare of moving goods in between locations of different layers e.g. suppliers to manufacturers, manufacturers to distributors, distributors to retailers and importers to distributors (Eq 47). This cost is product of unit transport cost and distance traveled and quantity transported.

$$TransC_t = \sum_{f,su,mu,l} UTCf_{f,l,t} \times dsumu_{su,mu} \times Qsumul_{f,su,mu,l,t} + \sum_{p,mu,du,l} UTCpmudu_{p,l,t} \times dmudu_{mu,du} \times Qmudul_{p,mu,du,l,t} + \sum_{p,du,ru,l} UTCpduru_{p,l,t} \times dduru_{du,ru} \times Qdurul_{p,du,ru,l,t} + \sum_{p,im,du,l} UTCpimdu_{p,l,t} \times dimdu_{im,du} \times Qimdul_{p,im,du,l,t} \quad , \forall t, f \in F, p \in P, l \in L, su \in g, mu \in g, du \in g, im \in g, ru \in g \quad (47)$$

2.6.2. Infrastructure cost

The existence of supplier ($Ysu_{su,t}$), manufacturer ($Ymu_{mu,t}$), warehouse distributor ($Ydu_{du,t}$), retailer ($Yru_{ru,t}$) and import ($Yim_{im,t}$) facility is calculated by the model economics and material balance criteria. These binary variables will take value of 1 if the optimizer chooses them, otherwise 0. If the value is 1, these get multiplied by their establishment costs, which has utility costs included in them for that time period (Eq 48). As the demand is different at different time periods, these binary values may or may not be same for each time period (Tables 11 – 15). As per assumption 10, transport infrastructure cost is not included during calculations.

$$InfraC_t = \sum_{su} Ysu_{su,t} \times Csu_{su,t} + \sum_{mu} Ymu_{mu,t} \times Cmu_{mu,t} + \sum_{du} Ydu_{du,t} \times Cdu_{du,t} + \sum_{ru} Yru_{ru,t} \times Cru_{ru,t} + \sum_{im} Yim_{im,t} \times Cim_{im,t} \quad , \forall t, su \in g, mu \in g, du \in g, im \in g, ru \in g \quad (48)$$

2.6.3. Storage cost

Storage or inventory facility has been assumed to exist at distributer locations only. The inventory holding cost is the product of unit cost and holding inventory (Eq 49).

$$InvtCdu_t = \sum_{p,du} invtdu_{p,du,t} \times UICdu_{p,du,t} \quad , \forall t, p \in P, du \in g \quad (49)$$

2.6.4. Production cost

It is assumed during the design that each manufacturing facility can have all four technologies to process four types of feeds. The unit cost of production $Cprod_{p,t}$ implicitly involves the cost of different technologies used and is multiplied with quantity produced $Pmu_{p,mu,t}$ (Eq 50) to get the production cost . However, all kinds of raw materials are not available everywhere. The optimal choice of technology will, therefore, be based on the raw material availability at a particular region and the technical feasibility of choosing a particular technology driven by the NPV of the project.

$$PrdnC_t = \sum_{p,mu} Cprod_{p,t} \times Pmu_{p,mu,t} \quad ,\forall t, p \in P, mu \in g \tag{50}$$

2.6.5. Import cost

Import cost is calculated by multiplying unit import cost with imported quantity (Eq 51) to meet the rising demand and maintain the final product RON (Eq 33). If demand is not satisfied, the loss to economy is on higher side than the cost incurred due to imports. Therefore, ethanol imports are integral part of SC to avoid any such penalty.

$$ImpC_t = \sum_{p,im} UImC_{p,t} \times import_{p,im,t} \quad ,\forall t,\ p \in P,\ im \in g \tag{51}$$

The above mentioned costs in section 2.6 are the most prominent cost components calculated in a SC that indirectly includes general cost, utility cost, power cost, labor cost and total product cost. In a way, NPV equation implicitly takes care of fixed capital and working capital investments.

3. Data collection for Indian scenario

The parameters used in the equations tailored for Indian scenario are discussed in this section. Most of them are collected from several sources of the government sites whereas few are derived. The values for the list of scalars (Table 7) are given in Table 16.

3.1. Demand data calculation for product

All the Indian states along with union territories are clubbed into 6 zones (Table 4). The population data used here is as per the latest census data (Ministry of Home Affairs & India, 2011). Assuming the rate of increase in population at these zones is not drastically changed over time, the percentage of population for each zone with respect to the entire country is calculated (Table 17). The fuel demand has been divided among these zones assuming the demand is proportional to population. As per the regulation by government of India, the blending of gasoline with ethanol should be 20%. Hence 20% fuel grade ethanol demand is calculated for the years 2018 - 2026 (Table 2). Further, the obtained overall ethanol demand is divided as per population percentage of each zone to calculate the corresponding ethanol demand for all six zones (Table 18).

3.2. Feed to product yield

Based on availability of feed at different locations, four types of feed (Table 3) are associated with different supplier locations (Table 19) and assumed to have unique technology for conversion. Few supplier locations such as g_7, g_9 and g_{18} can provide more than one feed. This helps the manufacturer to acquire feeds from nearby facility rather than moving far resulting in reduction in transport cost. The basic method for converting lignocellulose biomass to feed is hydrolysis followed by fermentation; however, based on difference in biomass feed composition, each process has unique set of operating conditions such as temperature, pressure, pH, enzyme to be used during pre and post treatment. Technology 1 uses two step modified process (Cardona et al., 2010), technology 2 uses simultaneous saccharification and fermentation process (SSF) (Wang et al., 2011), technology 3 uses isomerase mediated process (De Bari et al., 2014) and technology 4 uses ionic pretreatment process (Shafiei et al., 2013) (Fig 6). The corresponding conversion rates $conv_{f,tech,p}$ of feed to product are given in Table 20. Feed1 (bagasse) gives 236 liters of bioethanol with the help of technology 1 per 1000 kg of feed1. Similarly, other biomass feeds using corresponding technologies provide different yields from feed to product.

--- Figure 6 about here ---

3.3. Transport unit cost values

The distances between any two facilities have been obtained using digitized map and are shown in Tables 21 – 23. To calculate the distance between any two locations, the digitized map of google has been used. The minimum distance path is chosen for transporting goods. The flat distance of the earth's surface is known by the satellites of global navigation satellite systems (GNSS). The scales created by them is used by distance calculators (Dow et al., 2009).

To evaluate unit transport cost of biomass feed and ethanol product, diesel driven trains (5500 Hp engine) with 30 tank cars are used with each tank having a holding capacity of 30000 US gallons running with the speed of 40 km / hr. Similarly, large diesel trucks (350 Hp engine) with capacity of 30000 US gallons each running with a speed of 40 km / hr. are also used. The results for unit transport cost based on current diesel rates are given in Table 24.

3.4. Emission factor of pollution

To calculate the GHGe values in Eq. 39, first the system boundary of SC life cycle is established consisting of biomass cultivation, feed transport, biofuel production, product transport, biofuel storage followed by transport to retailers (Fig. 5), known as well to tank (WTT) approach (International, 2009).

The emission factors associated are given in Table 25. The average value estimated for fbc_f is 0.036 kgCO_2e / kg feed generated (Beeharry, 2001), which on derivation gives 60 tCO_2e / million kg or kiloton feed generated. The average value estimated for fp_p is 0.018 kg CO_2e / kg feed processed (Beeharry 2001), which on further calculation gives 152.54 tCO_2e / million liter product generated. The value estimated for inventory fdu_p is 5.75 kgCO2e / gallon ethanol (USEPA, 2018) which on derivation gives 15.47 tCO2e/ million liter product stored. The values for emission factor for transport $fsm_{f,train}, fmd_{p,train}$, $fimd_{p,train}$ and $fdr_{p,train}$ by train are directly obtained from literature (McKinnon and Piecyk, 2010).

3.5. Ethanol import cost, inventory cost and selling price

Since year 2013, the procurement price of ethanol is with oil manufacturing companies (OMC) and ethanol suppliers. The ethanol selling price $SP_{p,t}$ is considered as ₹. 43.7 / liter (Aradhey, 2017; Ahmad, 2018) for current time period and is calculated using moving average forecasting technique for the upcoming years (Table 26).

The $UICdu_{p,du,t}$ inventory holding cost per liter of ethanol is chosen to be 4% of the selling price for that time period (Peters et al., 1968). Imported ethanol $UimC_{p,t}$ is of higher RON with actual estimated cost for imported ethanol is 68% to 108% higher than indigenous cost, which lies between ₹ 73.92 and 91.52 / liter (Ahmad, 2018). For calculation, this value is considered as ₹ 75 / liter (Ahmad 2018).

3.6. Infrastructure cost

The cost of infrastructure considered here is holistic cost that is required to establish supplier, manufacturer, warehouse distributor with inventory, retailer and import facility along with their utilities like power consumption, water and labor etc. This type of cost mostly comes under the fixed capital investment (FCI) and is made as per strategic planning of SC, which can withstand for longer period of time. To estimate $Cmu_{mu,t}$, order of magnitude technique (Peters et al., 1968) is used, where similar kind of another lignocellulose plant is studied (Indiamart, 2018) and the corresponding cost is estimated by scaling up the plant capacity. The $Cmu_{mu,t}$ value for current year comes as ₹. 1.32×10^{9}. For determining cost values for upcoming years, the power factor x is applied to plant / capacity ratio as

$$C_t = C\times f\times R^x \quad (52)$$

where C is the cost for the previous year, f is cost index ratio of the current year to the previous year, R is the plant capacity ratio and x value is kept as 0.6 for chemical plants. Since the capacity R of the plant remains the same and the time value of money keeps changing with time, the cost index is obtained for previous years (Cost Index, 2018) and forecasted by adopting moving average technique for the upcoming years (Table 27). Once the cost index is known, the plant establishment cost, $Cmu_{mu,t}$ is obtained. As per FCI cost analysis, $Cmu_{mu,t}$ constitutes about 50% of FCI; supplier establishment cost, $Csu_{su,t}$ constitutes about 20% of FCI; distributor with inventory, $Cdu_{du,t}$ shares 15% of FCI; retailer cost, $Cru_{ru,t}$ with 10% and $Cim_{im,t}$ contributes 5% of FCI (Peters et al., 1968). These calculated values are used as data in the model (equation 52 is not used as equation in the model to avoid nonlinearity) and given in Table 27.

3.7. Feed, Production, Import, Inventory, intermediate quantity parameter values

The decision variables used in the SC model, $Feed_{f,su,t}$, $Qsumul_{f,su,mu,l,t}$, $Pmu_{p,mu,t}$, $Qmudul_{p,mu,du,l,t}$, $import_{p,im,t}$, $Qimdul_{p,im,du,l,t}$, $invtdu_{p,du,t}$ and $Qdurul_{p,du,ru,l,t}$ lie within certain bounds due to physical, technical, financial and resource limitations. The limitation can be feed availability, plant capacity, transport capacity, import capacity and inventory capacity.

$FeedMax_{f,su,t}$ is kept 3000 million kg or kilo ton per time period based on the various lignocellulose plant processing capacity throughout the country (Prakashan, 2018). Based on the corresponding demand data, the time period t is assumed as 1 year. Based on the minimum amount of feed to be processed by a technology, $FeedMin_{f,su,t}$ values are fixed. The value of $QsumulMax_{f,su,mu,l,t}$ cannot be greater than the feed available and is kept equal to

$FeedMax_{f,su,t}$ as one supplier can send maximum the entire available feed from supplier to manufacturer and $QsumulMin_{f,su,mu,l,t}$ is assumed as zero. The plant capacity varies from small, medium and large size with the capacity varying from 1000 - 10000 tons of cane per day (Prakashan, 2018). This gives an estimation for $PmuMax_{p,mu,t}$ value to be 1000 million liter per annum. Following production, $Qmudul_{p,mu,du,l,t}$ will be always equal or less than $PmuMax_{p,mu,t}$ and is assigned 1000 million liter per year.

In case the production is insufficient, the finished product is obtained from import facility with the maximum capacity of import, $importMax_{p,im,t}$ which is taken as 1000 million liter per year. $QimdulMax_{p,im,du,l,t}$ is always less that the $importMax_{p,im,t}$ with a value of 200 million per year so that the goods can reach more number of distributors instead of one. From operational point of view, there is need of safety stocks to be kept at the inventory locations in case of sudden increase in demand. So, the inventory values have been kept in the range of 1000 ($invtduMax_{p,du,t}$) to 10% of plant capacity ($invtduMin_{p,du,t}$) (Peters et al., 1968) per year at each facility. To match the demand values, the transport of $Qdurul_{p,du,ru,l,t}$ is kept at 200 million liter per year, less than $invtduMax_{p,du,t}$ so that a retailer can collect finished product from many distributors instead of one.

4 Results & Discussions

The model equations lead to an MILP, which is solved under GAMS® 24.1.3 environment using CPLEX solver. Two case studies have been considered. Case study 1 covers single mode of transport (i.e. train) with distance limitations. On the other hand, the second case studies the effect of adding another mode of transport (i.e. truck) with distance limitation on NPV. This case also includes several sensitivity studies on NPV e.g. the effect of change in number of zones, limitation on distance of feed movement, availability of feed supply, international ethanol price etc.

4.1 Case study 1

Table 28 shows the model statistics while providing solution for case 1 with 6 zones having inter facility distance limitation. The distances between supplier-manufacturer, manufacturer-distributor, distributor-retailer, importer-distributor are limited to 800, 1600, 1200, 2000 kms respectively. Several aspects of the obtained optimal SCN are highlighted below.

--- Figure 7 about here ---

4.1.1 Facility locations and connectivity

In response to the increasing demand of ethanol over the entire planning horizon, the increase in number of supplier, manufacturer and distributor with time is visible from Fig. 7. To handle this ever increasing demand, the algorithm adopted the strategy of increasing the number of facility locations to adjust the growth in material flow. This analysis clearly shows that many of the facility locations, which are not used in the initial years, are utilized later (Tables 29 and Table 11-15) showing the dynamic nature of SCN design over the entire planning horizon. In the initial years, when the demand is relatively less, certain network which can handle the situation becomes capacity limiting for later years. Here, the number of retailer locations are kept constant. This increase in number of facilities further increases the infrastructure cost over the time periods (Fig. 7 and Fig. 8c). For detailed connectivity, readers are instructed to refer Fig. 9 and Tables 30-33.

--- Figure 8 about here ---

4.1.2. Mass balance

The facility location and connectivity between nodes for the first time period, t_1, is shown in Fig 8. Out of the total 60 possible locations of the SCN super set, locations of 6 retailers in 6 zones are fixed and out of remaining 54 locations (3 potential nodes in each of the supplier, manufacturer and distributor layers for each of the 6 zones), only 30 locations are utilized for catering the demand at time period, t_1. Additionally, out of the 2 potential import locations, only one location has been utilized. As demand increases (~80% increase), number of free locations are

observed to diminish, which is visible through similar kind of figures for other time periods, say t_9, where 41 locations are utilized altogether (~36% increase). For the sake of brevity, these figures are, however, avoided and only the observed trend is mentioned. Out of 18 supplier locations, all of them are not observed to be used by the optimizer. Longer distance among these locations might be a reason behind not utilizing them as a result of which, the algorithm recommends the import of ethanol. Moreover, to maintain the quality issues of the final product, some amount of ethanol will be always imported.

To satisfy the demand, the manufacturing site selects the nearest feed supplier location as that leads to the least cost. In case, the nearest supplier is unable to provide the feed due to physical limitation, the model selects the feed from other supplier facility that can be from other zones as well, based on minimum transport cost. Moving to other zones might change the feed type and its corresponding composition based on geography. To tackle these unfavorable instances of feed supply composition at each time period, all four types of technologies are kept at each manufacturing sites to cover all possibilities. Use of technologies will be chosen by the optimizer. For e.g. at manufacturing facility g_{25}, technology 1 and 2 are used to process feed1 and feed2 for a time period t_2 and other two technologies are not used.

4.1.3. GHGe calculation

After calculating the emission factors and putting the same in Eq. 39, the calculated GHGe value comes as 3.9×10^7 tCO_2e for all considered years. Pollution contribution for this project per annum has been presented in Table 34. It can be seen that with increase in demand, the load on facilities and transportation increases, giving rise to more quantum of pollutants. It can also be seen that the carbon credit from the obtained optimal SC has a major contribution in the NPV (Table 34). To calculate the monetary value of GHGe savings, Eqs 40, 41 and 42 are used and the value $CCval_t$ is found to be ₹ 17×73 / tCO_2e (Bbc, 2010). The carbon credit thus calculated can be sold to the other nations, which are carbon credit deficient.

4.1.4. Cost Analysis

With increase in demand (Table 2), one can observe the increase in the costs of transport, inventory, production and imports as presented in Fig 8 (Table 35). At time period t_8, inventory cost and import cost are higher than the rest of time periods showing the proactive action for taking care of future demand by importing and keeping the product in inventory ahead in time. Pie chart in Fig. 8, showing the cost distribution, indicates that the major part of cost is production (~43%) followed by import (25%), transport (17%), infrastructure (15%) and inventory (0.43%). The similar trend is followed at all time periods (Fig 8h). Considering the higher cost of imports (₹ 75 per liter), the algorithm tends to extract as much from production (₹ 7 per liter) (Duffy, 2007; Sarrouh, 2007) compared to imports and thereby the production cost incurred is found more than that of imports, as per the intended plan. It would have been better if all the demand was met indigenously; however, that is never possible. The first reason is the physical limitation of feed availability. The second reason is the quality of final product needed (RON 95) is much higher as compared to the product quality of the ethanol produced indigenously (RON 85). Production alone cannot give the quality of RON, which makes high grade ethanol (RON 108.6) blending mandatory to achieve the desired RON.

Fig. 10 shows the total cost versus revenue at each time period. The money earned outweighs the cost to generate the profit and helps in achieving positive NPV. The selling price value kept by OMCs are such that it can take care of the investment made in the project including the newly implemented Indian goods and service tax (GST). The depreciation value obtained via sinking fund method is ₹ 1.276×10^{10} per annum for each year to give the final NPV of ₹ 1.37×10^{12}. NPV obtained in this case is a positive value indicating that the project is worth investing.

4.2 Case study 2

In the previous case study, the proposed model considered only single mode of transport and the feedstock is 100% available. This section will cover the sensitivity of using multi-transport facility, feed stock transport distance limitation, zonal distribution, feed availability, international ethanol price on the NPV.

4.2.1 Effect of additional transport mode on GHGe

Table 36 shows the emission factor for truck transport as continuation of Table 25. One can observe the increased value of emission factor for trucks with respect to trains. This contributes to higher GHGe (4.77×10^7, Table 37) for the same project compared to the case 1 (3.9×10^7, Table 34). The revenue generated via carbon credits is also reduced (2.81×10^{11} vs 2.92×10^{11}).

4.2.2 Effect of limitation on distance for transport mode, feed and product transport

Along with the distance limitation between facilities similar to case 1, distance limitation of 500 km on truck transport can be observed in Table 38. Mode of transport will be chosen by the optimizer based on NPV maximization. Given the lesser transport cost for train compared to truck (Table 24), train would be an obvious choice till the time its transport capacity is reached and trucks would be used for transportation thereafter. The first row (Table 38) shows the effect of using only train (as in case 1), where one can observe minimum transport cost and maximum NPV. The second row shows the effect of using only truck, where project incurs maximum transport cost and reduction in project NPV. When distance limitation of 500 km was imposed on the truck and both truck and trains were used, the transport cost of ₹. 2.25×10^{11} (4th row) was found to be less than ₹. 2.75×10^{11} when no such limitation was kept (3rd row). This happened due to more usage of truck as mode of transport.

While carrying out simulations with distance limitation on feed and product transferred, it was observed that better NPV is obtained by keeping restriction on distance travelled (Table 39). Lesser transport cost helps NPV to be significantly better (₹1.26×10^{12} compared to 1.08×10^{12}). This reveals the nature of bio supply chains, where supply chain locations, if placed near to one another, might lead to better NPV, which in turn leads towards increasing the number of zones from 6 to higher numbers.

--- Figure 9 about here ---

--- Figure 10 about here ---

<u>4.2.3 Effect of increase in number of zones</u>

To find the effect of number of zones spread across entire India, the existing 6 zones (Fig 4a) were increased to 12 (Fig 4b, Tables 40- 46). For both the cases, each zone has 3 suppliers, 3 manufacturers, 3 distributors. Additionally, the case of 6 zones has 6 retailers (62 facilities), whereas 12 retailers are considered for the case with 12 zones (122 facilities). With more numbers of nearby facilities appearing from 12 zones, a better solution with higher NPV has emerged compared to the case of 6 zones (Table 47). The reason can be attributed to the lesser transport cost (Eq 47) during OPEX calculation. The effect of lesser distance can be observed through lesser GHGe for 12 zones as well (Table 47 last row), providing more GHGe savings and higher GHGe revenues (Eqs 39 - 42).

<u>4.2.4. Effect of availability of Feed supply</u>

There exists practical difficulty in making biomass feed available at supplier locations for Indian scenario. In rural areas, pre-harvesting factors such as low per capita income, shrinking water resources, withering farming lands, lack of adequate and reliable electric power, absence of alternate efficient energy options, middle brokerage and lack of education are crucial hidden hurdles for biomass generation. Also 80% of the biomass is used as fodder for livestock, thatching house roofs, field burning or slashing, roadside dumping, traditional cooking and brick kiln making (Cardoen et al., 2015; Natarajan et al., 2015), leading to the post harvesting reasons of biomass feed stock unavailability. While simulating such practical situations, the feed ($FeedMax_{f,su,t}$) upper bound at supplier location has been kept at 3000 million kg at any time period and gradually reduced up to 20% of this maximum value to see its effect on NPV. As the feed supply reduces, the total production quantity decreases and the total import is increased to meet the corresponding demand deficit (Table 48). One can observe the decreasing trend in NPV with reduction in indigenous production. For 20% feed, the NPV obtained is negative clearly indicating that the project will be infeasible. Under the influence of negative NPV, to establishment bioenergy sector, financial support from Indian government is required at least during the initial phase of the project till breakeven point is reached or the government might facilitate the availability of the raw material by some administrative means.

4.2.5. Maximum Feed Supply versus Demand satisfaction

From Fig. 11, one can observe the effect of change (20 to 35%) in maximum feed availability $FeedMax_{f,su,t}$ along with demand satisfaction (0 to 100%) $Dem_{p,ru,t}$ on NPV. For 20% Feed, NPV changes from positive to negative at 50% demand satisfaction. With the current situation of feed supply, where 20% is available in real time scenario as discussed in previous section, only 50% demand can be met and to meet rest of the demand, one needs to increase import component. Similarly, for 25%, 30%, 35% Feed, NPV changes from negative to positive around 65%, 80% and 95% demand satisfaction, respectively. The trend shows that with increase in feed availability, more demand can be met and it becomes easier for the project to move towards positive NPV. For 40% available feed with varying demand values, the NPV obtained is always positive, indicating at least 40% $FeedMax_{f,su,t}$ and above must be always available at each supplier location to run the project successfully.

--- Figure 11 about here ---

4.2.6. Effect of International price fluctuation of ethanol

Fig 12 shows the effect of increase in international price of ethanol on NPV. Ethanol international price increase leads to increase in import cost which decreases NPV. As the model is linear in nature, the decrease in NPV shows a linear trend with percentage increase in international price of ethanol.

--- Figure 12 about here ---

All the results are unique and extremely useful for government as well as similar agencies interested in investing towards this sector. As the model uses demand data for future, the credibility of the model predictions depends on the type of forecasted data used.

5 Conclusions

A multi-period supply chain considering raw material suppliers, manufacturers, distributors and retailers has been designed for exploring the possibility of manufacturing bio-ethanol from the 2nd generation biomass in India to meet the government's aim of blending ethanol with gasoline. The novelty of the proposed SCN is that it can handle features such as (i) multiple types of feed based on geography, (ii) multiple types of manufacturing technologies at every location based on feed stock availability, (iii) multiple transport options, (iv) Greenhouse gas emission (GHGe) calculations to earn carbon credits to create extra source of income in NPV calculation as per Kyoto protocol, and (v) blending with imports. The imported ethanol can specially serve the dual purpose of meeting unmet demand due to insufficient production and enhancing the quality of the bio-product by blending.

Considering the forecasted demand data spread over multiple time periods, the MILP model predicts the structure of the SCN and their associated transport, storage, production and import decisions using a combination of binary and continuous variables towards maximizing the NPV. The characteristics of the SC model have been discussed considering distance limitation on single mode of transport for a planning horizon of 2018 – 2026 in the first case study. The second case explains the sensitivity of various factors influencing the NPV such as modes of transports, distance limitation on feed and product transport, change in number of zones, limitation of transport of feeds, extent of availability of feed and international price fluctuations. The following trends are observed:

- Increasing demand (80% increase over the planning horizon) over years made the supply chain structure changing with time, which leads to 36% increase in the newly added locations.
- With increase in demand, loads on facilities and transportation increase, giving rise to more quantum of pollutants.
- Among all other cost components, production cost is the highest (~43%) followed by import (25%), transport (17%), infrastructure (15%) and inventory (0.43%) costs.
- Physical limitation on feed availability does not allow the SCN to meet full demand through indigenous production. Moreover, to maintain the quality of the final product, some amount of ethanol would be imported always.
- Multiple modes of transport and increase in international ethanol price keeps NPV down.
- Feed stock transport of smaller distances and increasing the number of zones lead to more NPV.
- Feed availability 20% or below of the capacity limit makes the project infeasible. At least 40% of feed supply is needed to meet the projected demands.

The proposed model on non-conventional renewable biomass based biofuel economy will not only assist to curb the increasing conventional non-renewable fossil fuel demand and lower the economic burden on the country, but also help in reducing the pollution emissions leading to lower greenhouse gas emissions (GHGe) in the long run. This way the work can help in the maintenance of the environmental balance benefiting the health of the future generation. Enhancing the capability of the proposed deterministic SC model to handle uncertainty in demand could be a possible extension for the future work.

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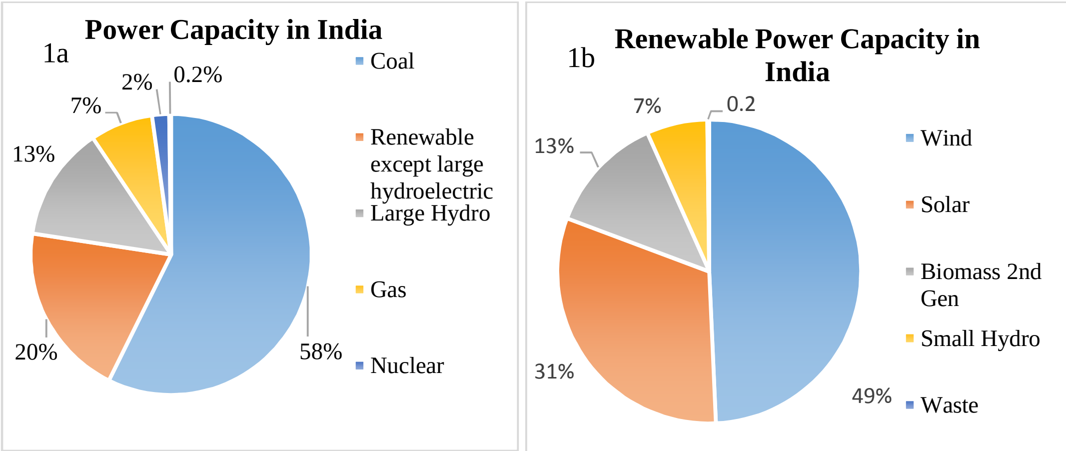

Figure.1. (a) Overall distribution of power generated from various sources in India; (b) Distribution of power generated only from different renewable sources in India.

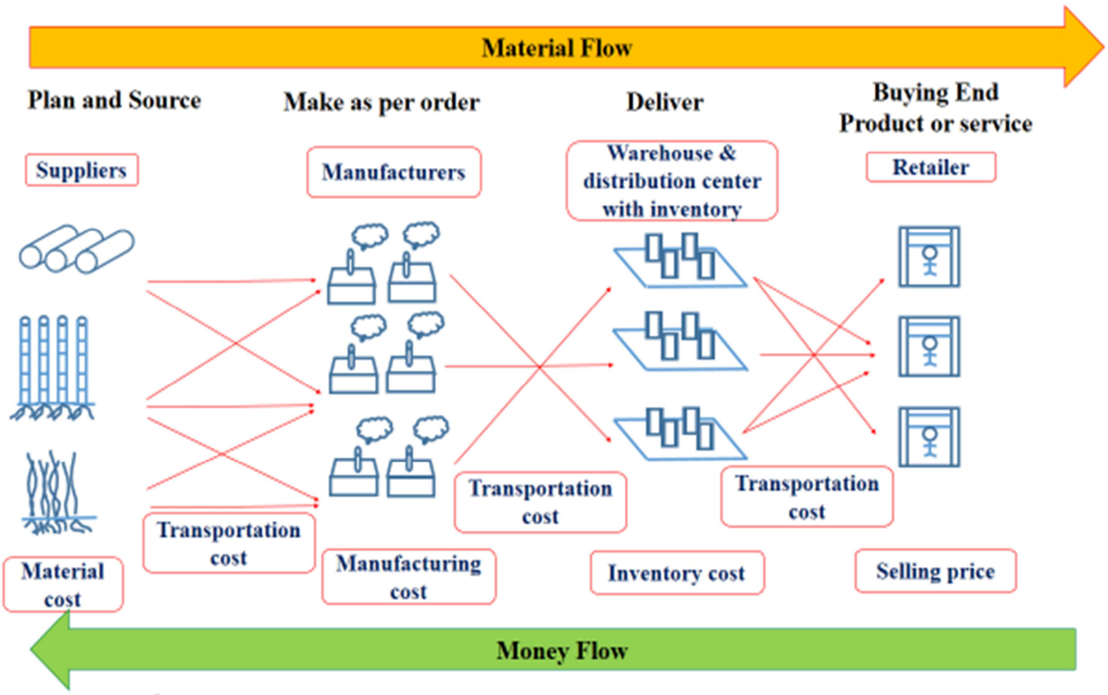

Figure 2. General overview of Supply Chain Network Design

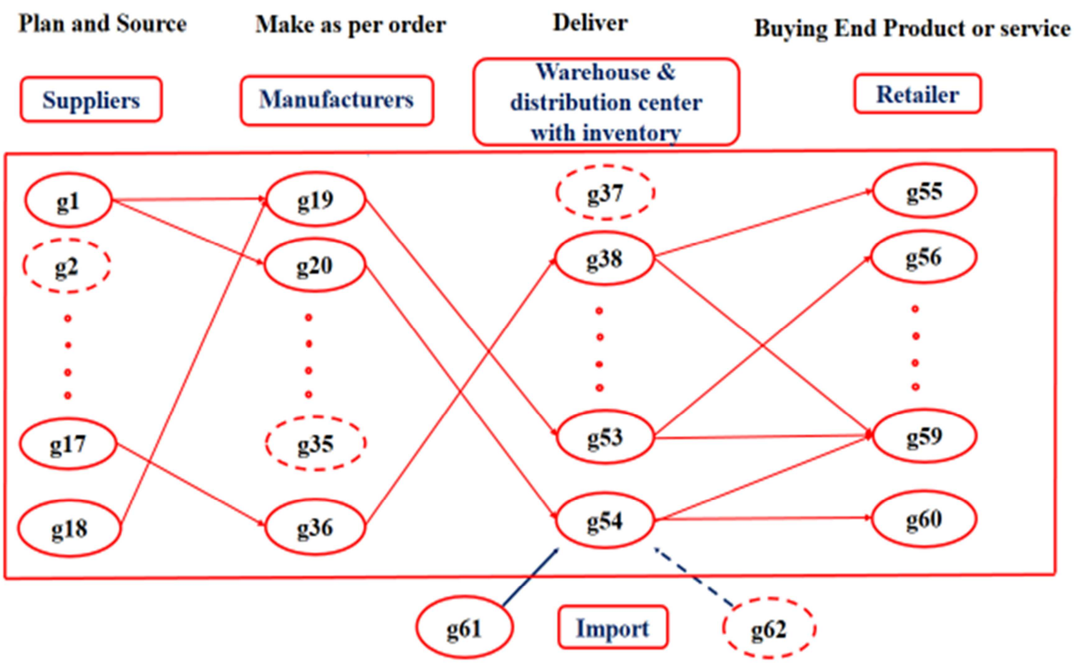

Figure 3. Model specific view of Bio SCN Design (SCND). The solid oval represents existence of node (binary 1) and dotted oval represents the absence (binary 0).

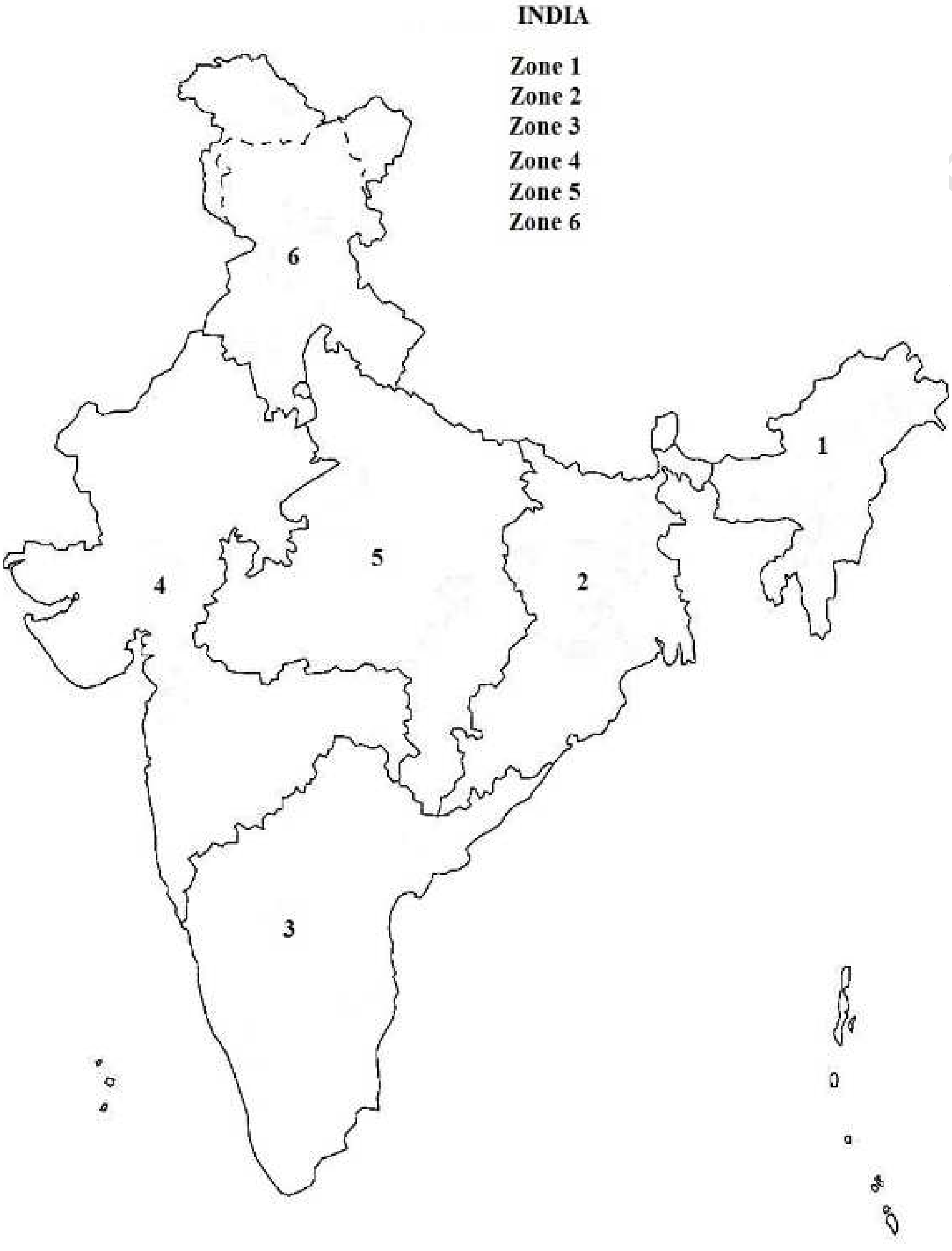

Figure 4a. Indian geography divided into 6 zones in case 1 (Table 4)

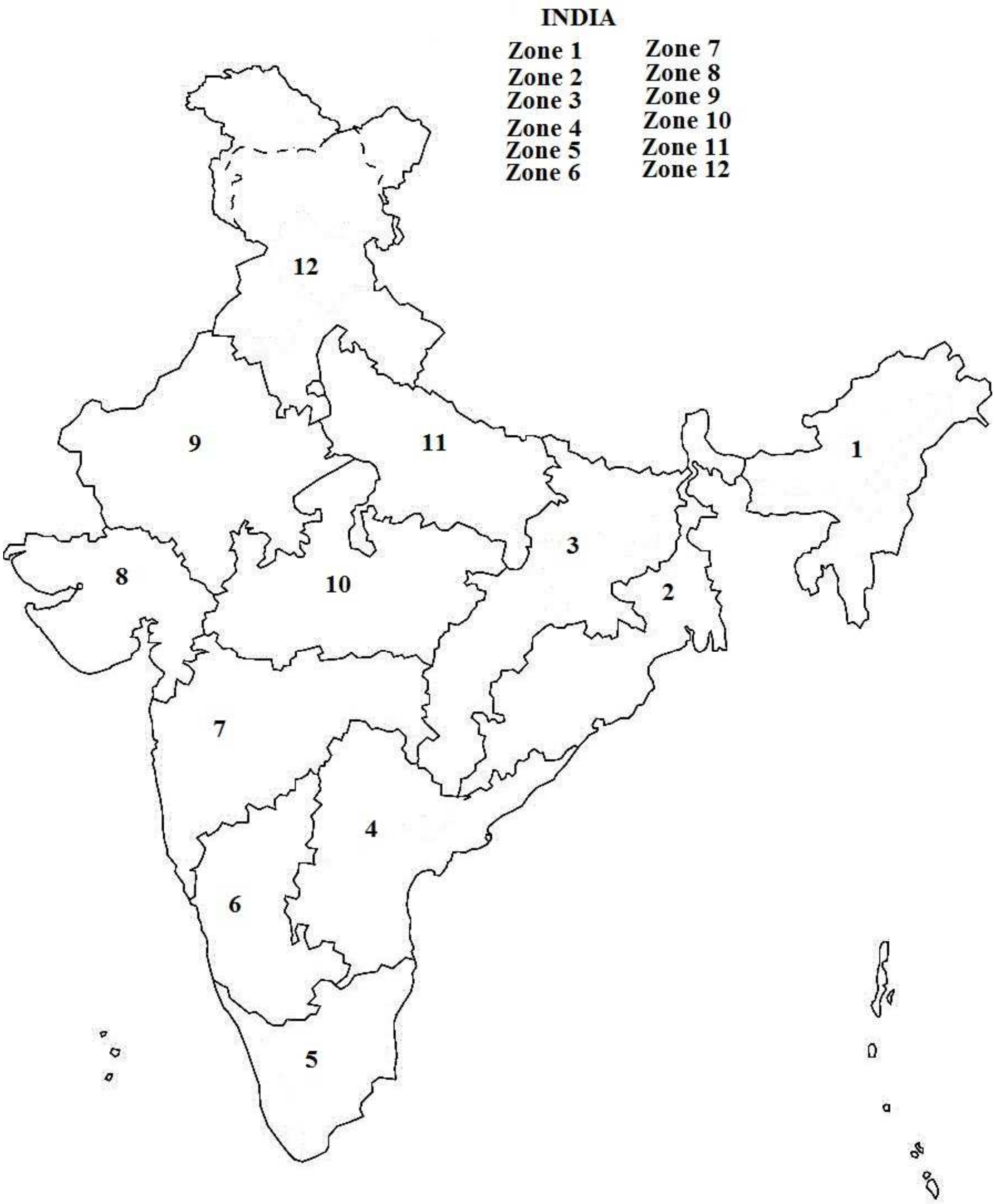

Figure 4b. Indian geography divided into 12 zones in case 2 (section 4.2.3)

Figure 5. Life cycle stages of SC based on well to tank approach

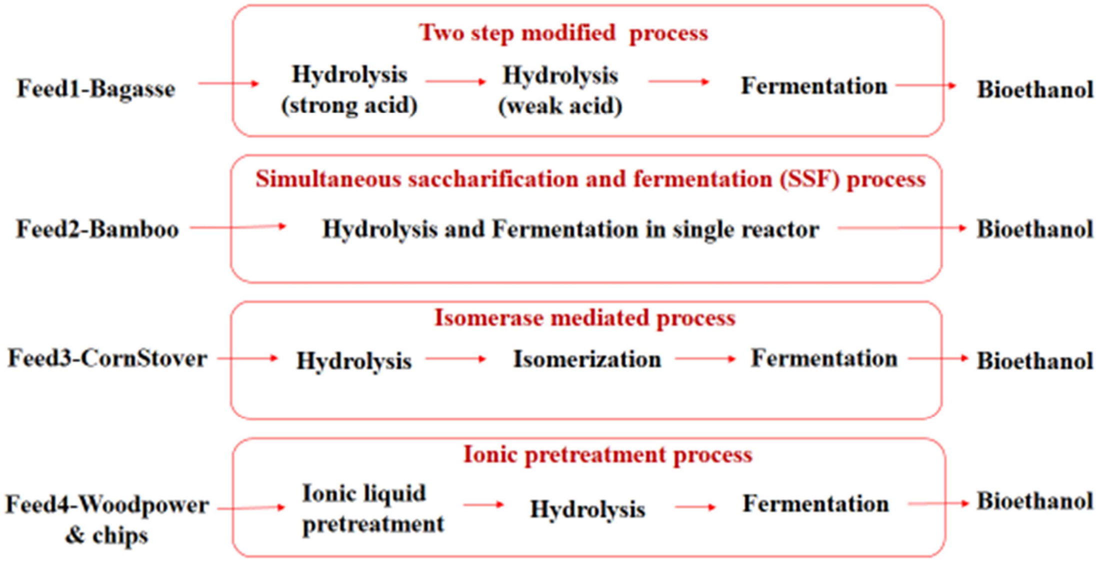

Figure 6. Different process technologies to produce bioethanol from different sources of lignocellulose biomass

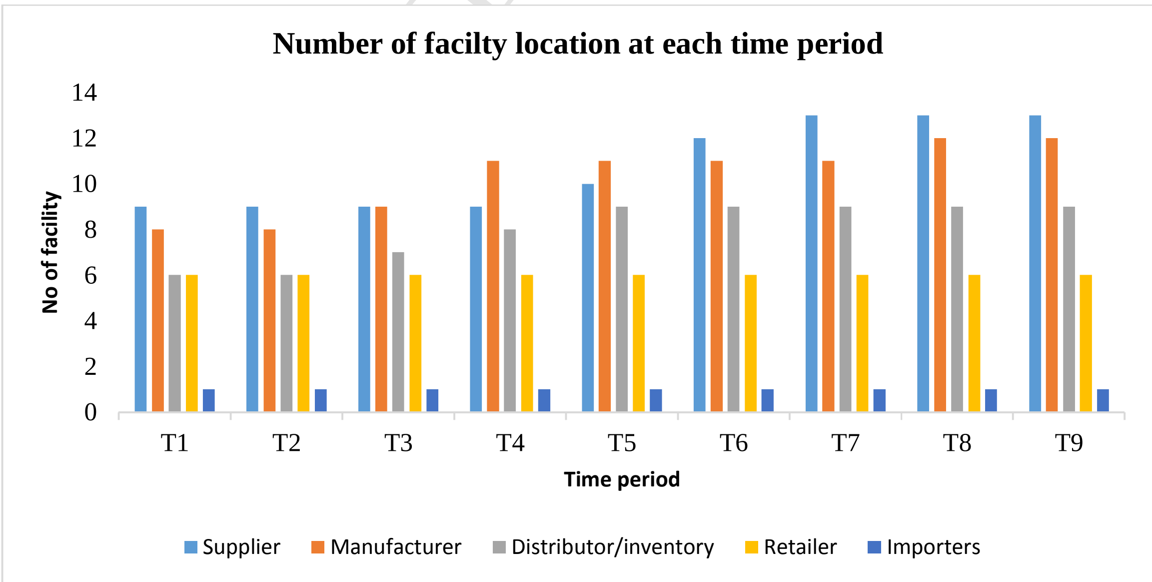

Figure 7. Increasing trend in facility location numbers with time for 6 zones. The number of retailer are kept constant.

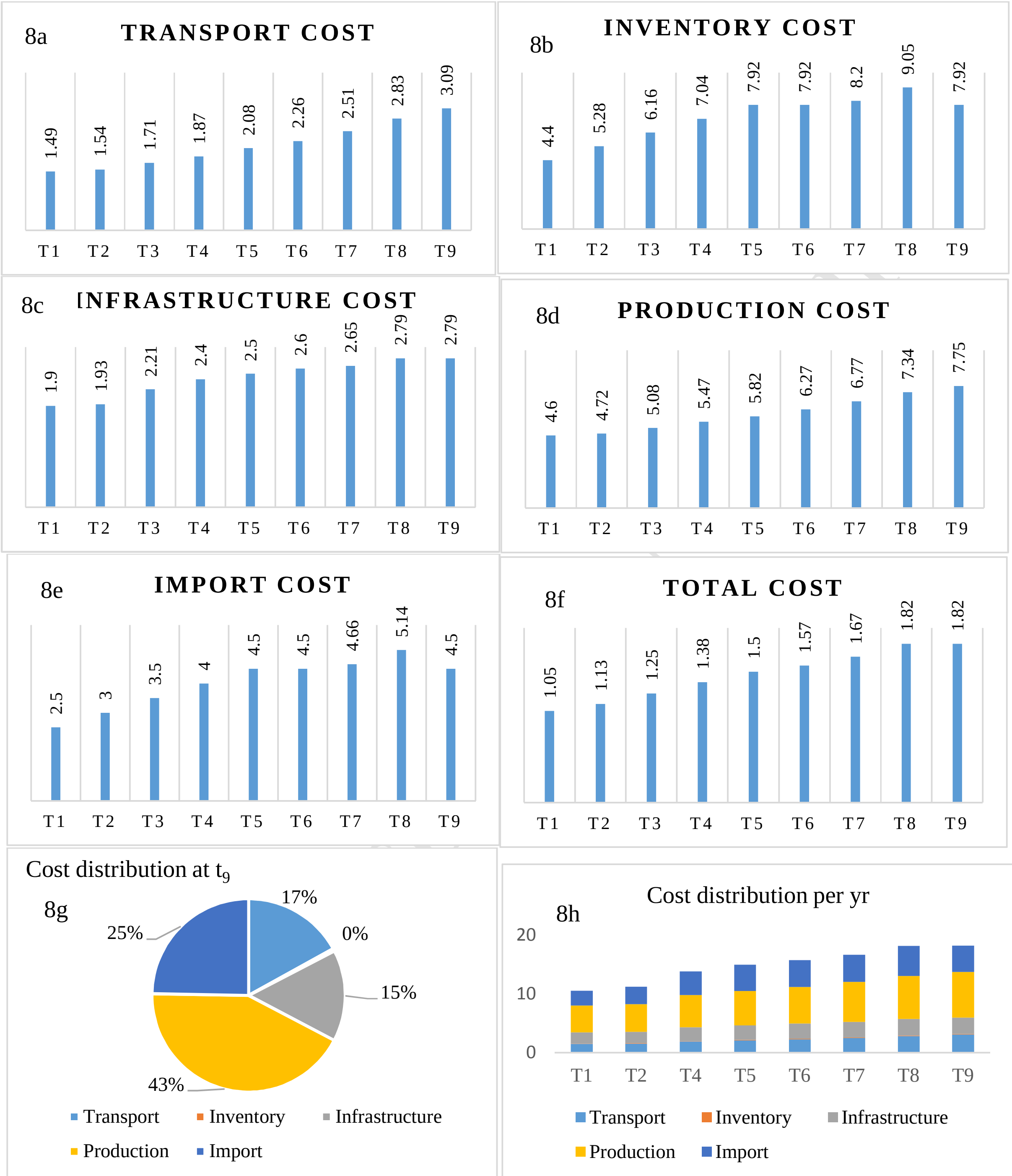

Figure 8. Cost analysis for case study 1 in ₹. 8a. Transport cost for each time period (in ₹ 10^{10}); 8b. Inventory cost (in ₹ 10^{8}); 8c. Infrastructure cost (in ₹ 10^{10}); 8d. Production cost (in ₹ 10^{10}); 8e. Import cost (in ₹ 10^{10}); 8f. Total cost (in ₹ 10^{11}); 8g. Cost distribution for last time period t_9; 8h. Total cost distribution among all time periods (in ₹ 10^{10})

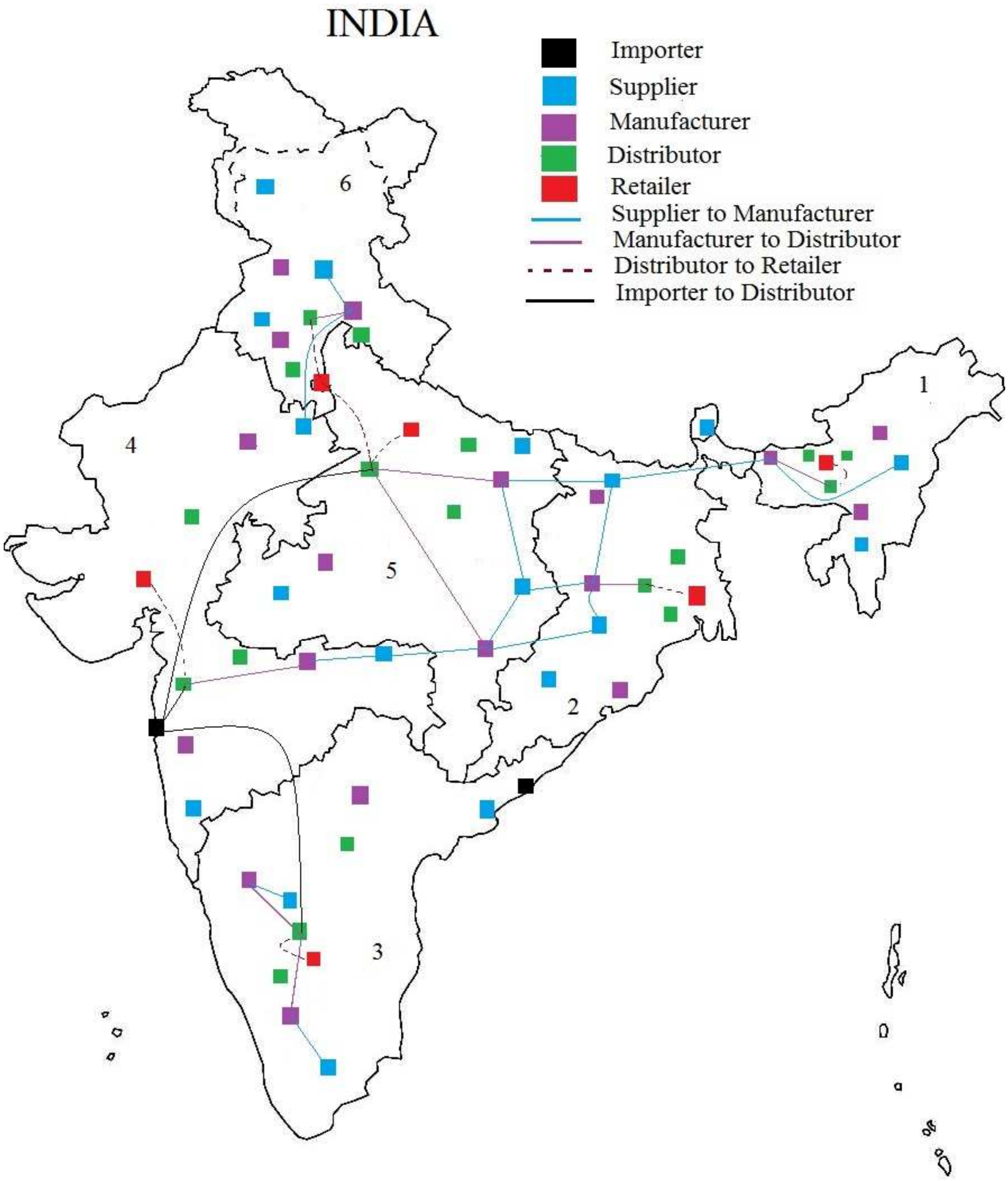

Figure 9. Interconnectivity between nodes of different layers for case1 at time period t_1 where connections are allowed across the zones to meet the demand at retailers (shown as red filled boxes). Only used facilities are connected. Number indicates zones as in figure 4a.

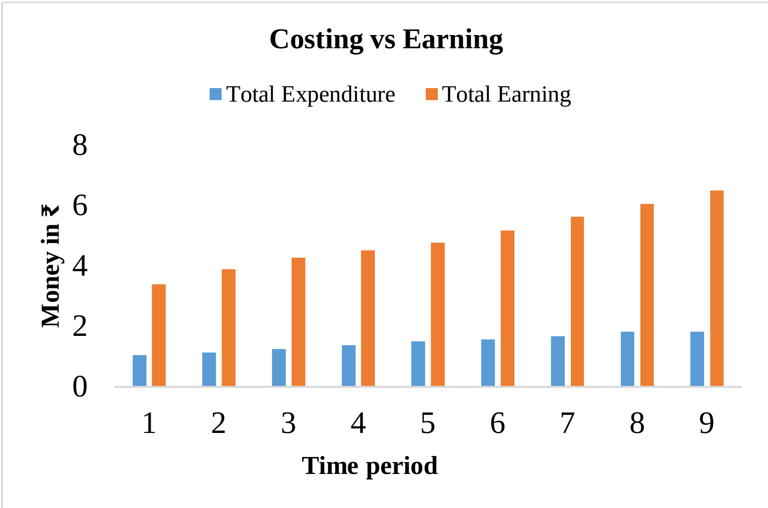

Figure 10. Total cost incurred and revenue generated during each time period in ₹(in 10^{11})

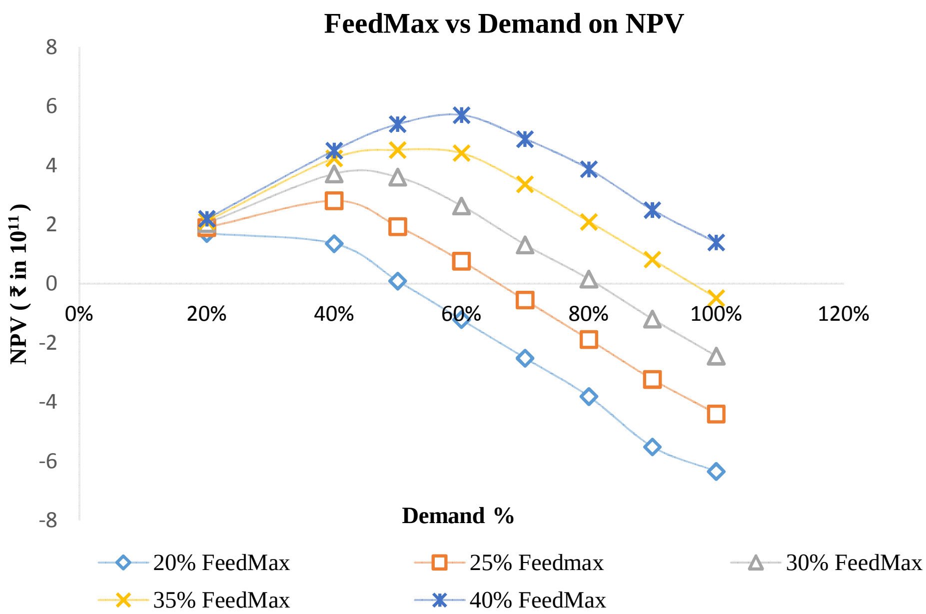

Figure 11. Effect of maximum feed availability and demand satisfaction on NPV

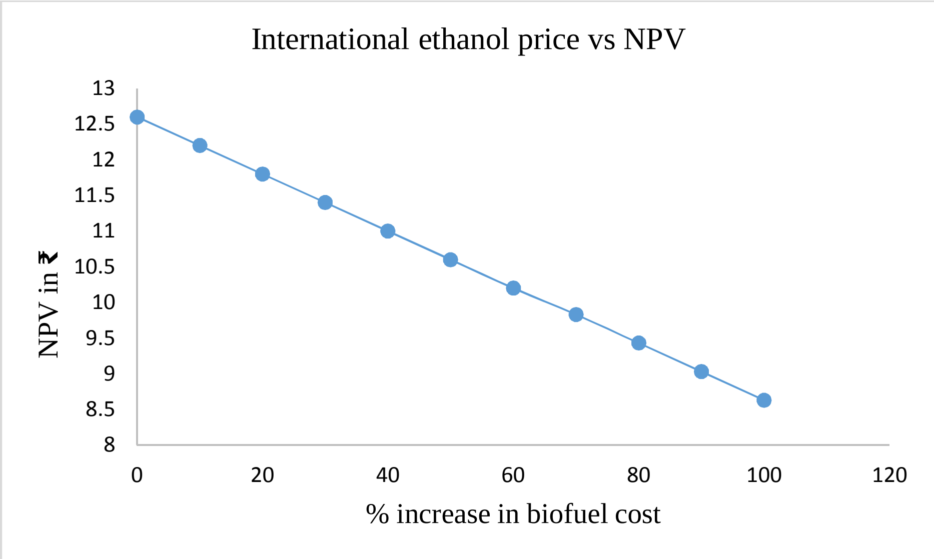

Figure 12. Effect of international ethanol price increase on NPV.

Highlights

- MILP frame work for NPV using newly implemented goods and service tax (GST)
- Decentralized model zones based on population data and feed type availability
- Blending indigenous bioethanol and imported ethanol for desired RON quality
- Revenue generation from greenhouse gas emission (GHGe) savings as carbon credits
- Sensitivity analysis of distance, international price and feed availability on NPV