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Multiscale Strategic Planning Model for the Design of Integrated Ethanol and Gasoline Supply Chain

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The design and planning of an integrated ethanol and gasoline supply chain is addressed, and is composed of harvesting and production sites for ethanol, petroleum refineries, distribution centers where blending takes place, and the retail gas stations where blends of gasoline and ethanol are sold. We postulate a superstructure that combines all the components of the supply chain and different means of transportation, and model this multiscale design problem as a multiperiod MILP model. In order to identify regions where investments are needed and the optimal configuration of the network, a strategic planning model is considered in which gasoline stations are aggregated in different regions. A detailed formulation is considered where regions are disaggregated into gas stations to determine the retrofit projects for the selection of blending pumps over their expected life. Also, the application of these MILP models with two large-scale problems are illustrated. *AIChE J*, 59: 4655–4672, 2013
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Introduction

During the last decade the increasing concern on limited fossil fuels and environmental issues has brought attention to ethanol as a major energy source from biomass. Ethanol can help to address the need for new liquid fuels as complement of fossil fuels for the next decades. Furthermore, ethanol is the most promising liquid fuel that stands for the commitment of the renewable fuel standard (RFS), part of the Energy Independence and Security Act of 2007 from the US, where the goal is to accomplish the production of 16 billion gallons of cellulosic biofuels by 2022.[1,2] The feasibility of introducing ethanol in fuel markets has already been proved.[3] Currently, blends of gasoline and ethanol can be used by more than 80% of the current light-duty transportation vehicles.[4] Some ethanol production technologies have already been developed and are being improved with the purpose of making ethanol more competitive as compared to gasoline, and releasing the dependence on governmental subsidies. Along this line, Martin and Grossmann[5] have optimized production processes taking into account the use of raw materials, water and energy for first, second and third generation of biofuels. Vimmerstedt et al.[6] have used a systems dynamics approach to provide a framework to execute subsidies policy, focusing on the downstream supply chain. These authors conclude that subsidies are required for the distribution and dispensing infrastructure to introduce high-blend ethanol into fuel markets. Akgul et al.[7] have analyzed a hybrid first/second generation biofuel supply chain, taking into account trade-offs between economic and environmental objectives.

However, there are other challenges that have not yet been solved. Main concerns are related to the downstream supply chain, where petroleum and ethanol industries must be coordinated when blending their products. Other issues of concern are related to biomass transportation, supply chain design of bioethanol and its integration to gasoline supply chain. Wakeley et al.[8] evaluate the transportation effects for the production of E85 (a blend of 85% ethanol and 15% gasoline) by a combination of corn and cellulosic ethanol and recommends regional concentration of E85 blends to reduce costs. In the areas where feedstock sources are not easily available, these authors recommend to explore other fuel alternatives. Ethanol transportation by truck is especially useful to reduce storage requirements at biorefineries because it offers more flexibility to accommodate to uncertain market demands (US Dept. of Agriculture). Eksioglu et al.[10] analyze logistical challenges on the biomass distribution and supply. They conclude that when biomass availability is low and transport costs are high, smaller size biorefineries become economical. The integration of ethanol and gasoline has been studied by Russell et al.[11] who focus on the logistics management process, railway transportation and intermediate storage. Furthermore, recent reports of NREL, DOE and USDA analyze the impact of blending ethanol and

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gasoline.[2,12] To address some of the issues investigated, Russell et al.[11] propose the use of intermediate hub storage to better complement railway transportation, the building of strategic relationships among petroleum distribution centers, ethanol producers and transportation providers.

Supply chain problems are often modeled as mixed integer linear problems[13] (MILP), which can become intractable due to their size.[14,15] To overcome this issue, decomposition strategies are applied, such as Lagrangean decomposition, Benders decomposition and bilevel decomposition. Iyer and Grossmann[16] address the long-range planning with a bilevel decomposition algorithm where the higher level problem determines the processes that should be selected and the capacity and production planning are determined at the lower level problem. Since the former provides an upper bound for the profit and the latter a lower bound, these subproblems are solved iteratively by adding cuts until the bounds are within a given tolerance.

In this work, we propose MILP models for the design of the integrated supply chain of ethanol and gasoline, and we apply a bilevel decomposition algorithm to reduce the computational expense. The article is organized as follows. In the next section, the background to gasoline and bioethanol supply chains is provided. The problem statement is then presented. The MILP formulation, where constraints for harvesting sites, ethanol plants, distribution centers, retail centers and objective function are described next. Finally, examples are presented for the aggregated and detailed models. Numerical results are discussed and compared. The decomposition algorithm and computational time for the detailed model are discussed in the supplementary material.

Background

The petroleum supply chain is often divided into two major components: upstream and downstream. It can further be classified into different stages such as exploration and extraction itself, petroleum refining and retail consumption. These stages are illustrated in Figure 1.

The different echelons of the supply chain are connected to each other, mainly by pipelines. The petroleum extracted at the very beginning of the chain is transported to crude oil terminals. These terminals supply refineries with crude oil, where it is transformed into an assorted set of products. One of the interests in this article is gasoline, which is transported to distribution centers and then sent to retail centers. The petroleum pipeline network is well developed within the US, and most transportation in the petroleum supply chain takes place by pipeline.[17,18]

A general scheme of the bioethanol supply chain is illustrated in Figure 2, where the raw material (either first, second or third generation) is harvested and sent to collection facilities or ethanol plants. Collection facilities feed the ethanol plants with biomass.[19] Once ethanol is produced, it is sent to distribution centers for storage and blending with gasoline. Finally, distribution centers send ethanol blends to retail centers (gas stations). Transportation in the ethanol supply chain is mainly carried out by trucks, even though there is the possibility to use railways, even from the collection facilities.[20]

The multiple warehouses at distribution centers level are placed so as to take advantage of railway transportation. Therefore, in many cases intermediate warehouses are needed depending on the existence of railway facilities in ethanol plants and in retail centers.[11]

The ethanol supply chain must be coordinated with the gasoline supply chain in order to manage a lower cost ethanol blend.[21] The integration of these two supply chains is addressed to carry out a cost-effective coordination. Since the main focus of the model is on the downstream of the supply chain, upstream details such as selection of collection facilities have been simplified. Figure 3 shows the integrated ethanol-gasoline supply chain considered in this article.

Within the harvesting sites, storage is required for the biomass. After this stage, the biomass is sent to the ethanol plants (or biorefineries) where bioethanol is produced through any of the technologies considered: biochemical, thermochemical or a hybrid technology between these.[5] Ethanol is transported to the distribution centers, which in turn receive gasoline from the refineries. The distribution centers feed the retail centers with the fuel blends required by the market, mixing or not E85 and gasoline. Our model considers that the lowest ethanol blend at retail centers should be E10, which is currently the gasoline that is sold in most of the US gas

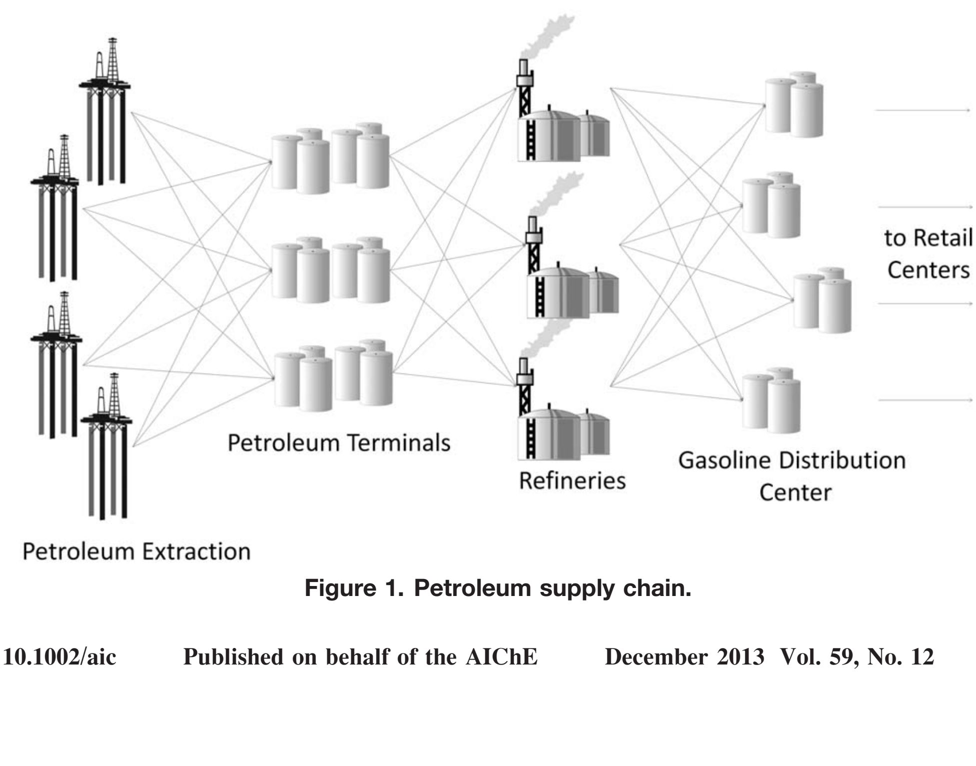

Figure 1. Petroleum supply chain.

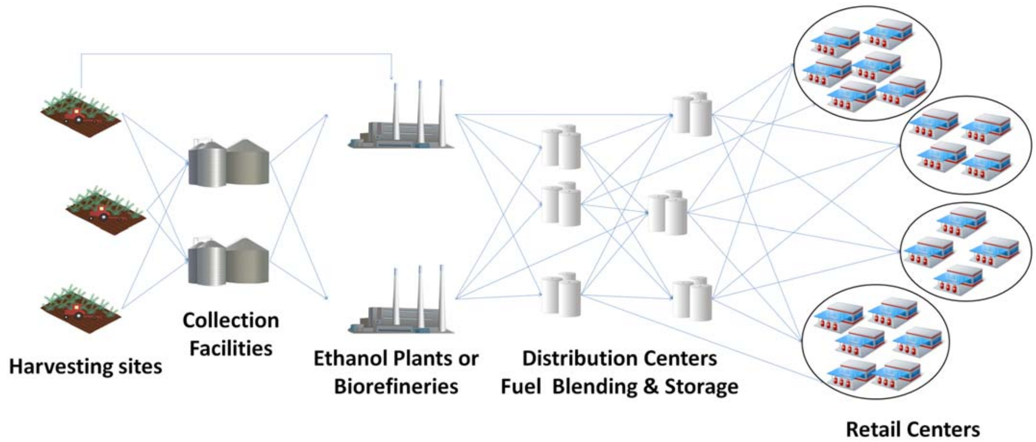

Figure 2. Ethanol supply chain.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

stations. Retail centers represent a group of gas stations, where every fuel blend can be fed and stored in underground tanks. Some gas stations sell only the fuel blends they receive, while others can blend the fuels stored in their underground tanks to produce alternative blends using blending pumps operated by the consumers. Blender pumps allow the consumer to select between several ethanol blends, according to the brands preprinted in the fuel pump. Figure 4 shows how blender pumps work for the case when E10 and E85 are stored in the tanks with the possibility of producing the E30 blend.

The advantage of blender pumps is that they allow having a set of several blends available to consumers. While their fixed capital investment is higher than the required for a normal gas station, it is much lower than the investment required having each blend available separately with different tanks and facilities.

One of the main issues about selling several fuel blends in the market in the short term is to estimate the demand for each blend. This not only depends on the flexibility of the car fleet, but also on the driver's preference and activities, and on how the car performs with each blend in different types of trips (e.g., flat vs. mountain), and also on the relation between price and mileage for each vehicle. Given this situation, it is preferable to have a blending pump in a gas station because it allows the sale of several blends regardless of the product stored in the underground tanks.

Summarizing some of the issues discussed in this section, this work addresses the optimal design of an integrated ethanol and gasoline supply chain (Figure 3) that accounts for

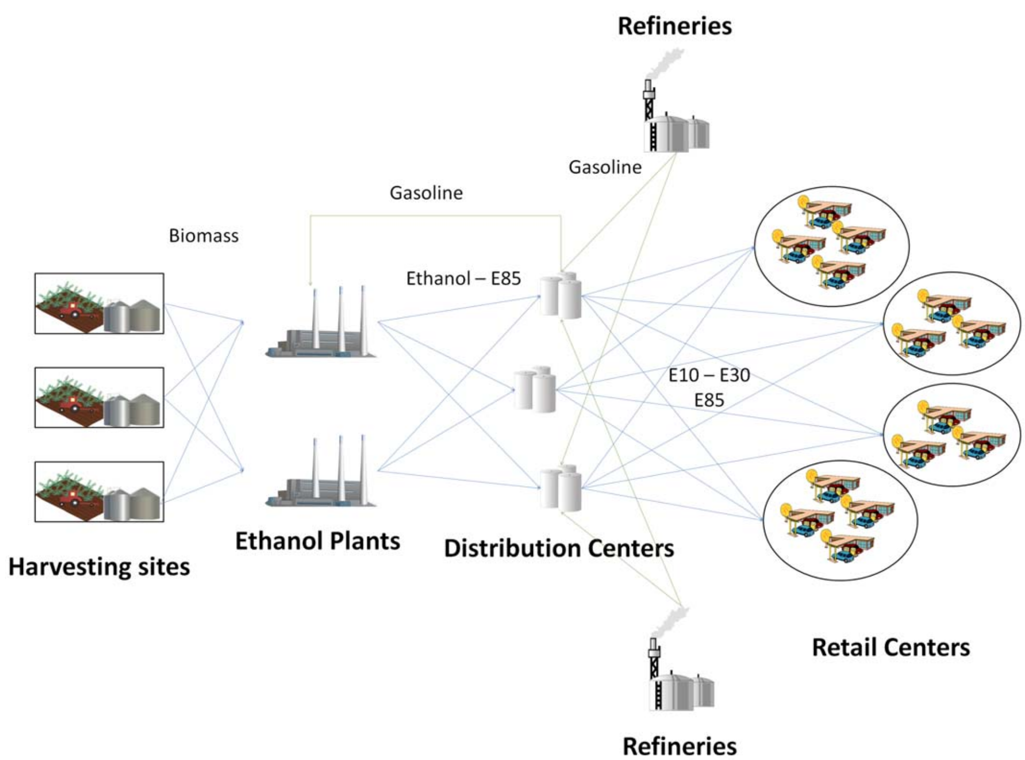

Figure 3. Superstructure of gasoline and ethanol supply chain.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

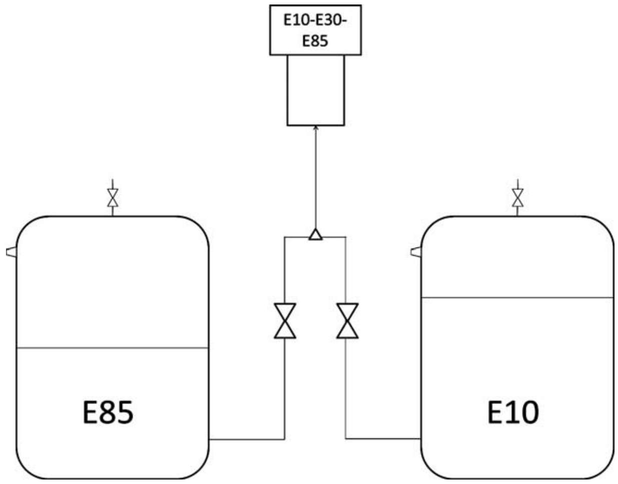

Figure 4. Blender pump scheme.

details in downstream operations and general characteristics of the upstream operations. A set of harvesting sites to produce the raw materials needed to obtain cellulosic ethanol, and a set of ethanol plants with different production technologies are considered. Also a set of distribution centers for gasoline and E85, or both products together, a set of refineries and a set of retail centers are considered. Mixing of fuels can occur within distribution centers or within retail centers, which are defined by a set of gas stations. Transport from refineries to distribution centers is only considered with pipelines. Railway and truck transportation is considered between ethanol plants and distribution centers.[22] For simplicity, blends considered in this model are: E10 (currently used in U.S.), E30 and E85. However, the model can be easily extended to consider additional blends. Also, for simplicity we consider that the different grades of gasoline are aggregated into a single grade, although once again the model can easily accommodate multiple grades of gasoline.

Problem Statement

The problem addressed in this article is based on the integrated superstructure of ethanol and gasoline supply chain shown in Figure 3 and is stated as follows: Two different types of biomass are considered; wood residues and switchgrass.[23] After harvesting, drying and intermediate storage are required. We assume that these operations occur within the same location of the harvesting site. Biomass transportation to biorefineries, which is a significant bottleneck of the supply chain due to the biomass low density, is carried out mainly by trucks. Biorefineries produce ethanol and E85, which is composed of 85% ethanol and 15% gasoline. A percentage of the ethanol produced is consumed by other industries, and E85 blend is sent to gasoline distribution centers. Gasoline is produced at the refineries and sent to the gasoline distribution centers, which in turn can feed ethanol plants as it is shown in Figure 3. The E85 blend from the ethanol plants and gasoline from the oil refineries are transported to the gasoline distribution centers to produce different blends (E10 or E30) in order to supply them to retail centers. Blending of ethanol and gasoline can occur at the distribution centers or in the retail center itself. Sales of E10, E30 and E85 take place at the retail center. We consider a time horizon of several years during which demands are specified for E10, E30 and E85. The total demand of fuel is estimated from the average fuel consumption published on 2002 Economic Census.[24] For each blend we assume that the demand is given by a percentage of this total demand.

We formulate two models of different levels of detail. The first one is an aggregated model that considers the fuel demand per region without details of the gas stations. In contrast, the second model considers the number of gas stations per region. Since the only difference between the two models is at the retail centers, the description of the other stages in the supply chain (harvesting sites, ethanol plants and distribution centers) is the same for both models. Existing and potential capacity for the ethanol plants, refineries and distribution centers are given. Different means of transportation are available for each product (truck, railway and/or pipeline).

At each stage of the supply chain the following information is given.

- For each harvesting site and both sources of biomass, we are given the capacity of dry feedstock production. We consider harvesting fields and storage facilities in the same node of the supply chain because the article focuses on the downstream of the supply chain (retail centers and gas stations).
- For each potential ethanol plant in both models, we consider three available technologies: biochemical, thermochemical and hybrid (gasification + fermentation) with three different levels of investment, taking advantage of the economy of scale: small, medium and large (50,000, 100,000 and 150,000 ton/y, respectively). For each one, we are given existing capacity and yields.
- For each potential distribution center in both models, we consider three different levels for the investment. Also blending of E85 and gasoline can take place to produce E30 and E10 blends.
- Finally, for each retail center in the aggregated model, we consider the fuel demand of every blend (E10, E30 and E85), frequency of replenishment, initial capacity and investment cost.
- For each retail center in the detailed model, we consider the possibility of installing blending pumps through retrofits.[25] Retrofits on each gas station are mandatory every 10 years, and between they are optional. Additional data are: fuel demand of every blend (E10, E30 and E85), frequency of replenishment, initial capacity, number of existing gas stations, average capacity of underground storage in gas stations, investment cost for new gas stations, investment cost for retrofits on gas stations and the time required to carry out a retrofit or building of a new gas station.

Given the aforementioned information the following decisions must be made to design an optimal integrated supply chain:

✓ In harvesting sites (HS)
  - Location and production capacity
  - Which HS feeds each ethanol Plant

✓ In ethanol plants (EP)
  - Location
  - Technology of each EP installed and production capacity
  - Amount of ethanol produced between 50 and 100% of installed capacity
  - Interconnection between EP and gasoline distribution centers

✓ In gasoline distribution centers (DC)
  - Location and storage capacity
  - Level of Production of blends between 50 and 100% of installed capacity
  - Which Refinery feeds each DC
  - Which DC delivers gasoline for each EP
  - If E10 and E85 are mixed to produce blends (E30), or supply these products to retail centers

✓ In Retail Centers (RC) for aggregated model
  - Sales of fuel blends to satisfy the total demand

✓ In Retail Centers (RC) for detailed model
  - Number and type of gas stations (GS) in each RC
  - Operating GS to meet the demand in each time period
  - Schedule of retrofits over each GS and new GS needed
  - Sales of fuel blends to satisfy the total demand

In order to select these decisions, two multiperiod MILP models are proposed (aggregated and detailed) to minimize the total cost of the supply chain, which includes terms for capital cost, production cost, transportation cost, storage cost, distribution cost, and purchase cost of biomass and gasoline. To calculate these costs we have considered linear cost models with fixed charges.

The major assumptions in the proposed models include the following. The inventory level of product p is calculated through a specified number of replenishments per time period (Eq. 9 for ethanol plants). The amount stored of product p is bounded between one and three times the inventory level (Eqs. 10 and 11 for ethanol plants).[26–28] The turnover ratio considered is 2 weeks for ethanol products, 3 months for biomass, and 10 days for fuel blends in gas stations.

The final market of fuel blends is composed of gas stations. However, if we considered one retail center per gas station in the supply chain, the size of the problem would be very large. Therefore, in the detailed model, we let retail centers represent an entire county in which the gas stations are included. It is only necessary to keep track of the number of gas stations to somehow determine the capacity of the retail centers. We assume different types of gas stations classified by the products they can sell. This information is displayed in the first two columns of Table 1. There are gas stations that can only provide a unique blend (single product gas stations: G1 for E10 and G2 for E30), and those that can provide the customers with a set of blends (multiproduct gas stations, G3 for E10, E30 and E85) through the installation of blending pumps. Notice that the options of installing blending pumps are considered within the G3 category.

Every fuel blend in multiproduct gas stations (G3) must be produced by mixing the existing fuel blends stored in the underground tanks (this kind of gas stations can also provide customers with the fuel stored without mixing it). The same applies to the distribution centers. The equations describing the mixing process of distribution centers introduce, in principle, nonlinearities in the model. However, a linear model can be derived by computing mass balance coefficients that represent fractions of the gasoline and ethanol, or of E10 and E85 to obtain the E30 blend.

For investments on gas stations we assume that there could be new stations or retrofits of existing ones, as shown in the last three columns of Table 1. For example V2 retrofit involves the conversion from a G1 gas station to a G2 gas station, V5 retrofit involves a conversion from a G2 gas station to a G3 gas station, while in V6 retrofit investments are made to keep operating the same type of gas station, G3. We also assume that the gas stations have a specified lifetime after which they must undergo a change of tanks. At this point a gas station may keep supplying the same products (V1, V4 or V6), switch the products without large investments (V2) or else invest in additional tanks and blending pumps to produce additional products (V3 or V5). The different types of retrofits are listed in the last three columns of Table 1. Note that retrofits from G1 and G2 to G3 require installing blending pumps.

Furthermore, we consider the possibility to satisfy high ethanol blends demand with lower ethanol blends, as flex-fuel cars requiring E85 can also work with lower ethanol blends. However, a minimal quantity of each blend demand has to be fulfilled with that blend.

MILP Formulation

In this section we describe the multiperiod MILP models (aggregated and detailed) to optimize investments in the ethanol and gasoline supply chain.

Harvesting Sites

The mass balance of the harvesting sites is included in Eq. 1 and establishes that the amount of feedstock b produced in harvesting site i in time period t (bhs_{bit}) must be equal to the biomass sent to the ethanol plants j by transportation mode m ($qb^{IJ}{}_{bijmt}$)

$$bhs_{bit} = \sum_{j} \sum_{m} qb^{IJ}_{bijmt} \qquad \forall \ b, i, t \tag{1}$$

Equation 2 states that if in the harvesting site i the feedstock b is produced ($y^{I}{}_{bit} = 1$), then the amount produced (bhs_{bit}) should be less or equal to the total available quantity (AB_{bit}). This total amount is related to the level of production

$$bhs_{bit} \leq AB_{bit} y^{I}_{bit} \qquad \forall \ b, i, t \tag{2}$$

There is also an upper bound on the amount of transported biomass b by transportation mode m from harvesting site i in

Table 1. Types of Gas Stations and Retrofits

Type of Gas Station	Product produced	Type of Retrofit	Original type of GS	Final type of GS
G1	E10	V1	G1	G1
		V2	G1	G2
G2	E30	V3	G1	G3
		V4	G2	G2
G3	E10; E30; E85	V5	G2	G3
		V6	G3	G3

time period t. This upper bound takes into account a maximum number of units in transportation mode m (trucks or freight car) and their corresponding weight capacity.

Ethanol Plants

The inventory balance for biomass in ethanol plants in Eq. 3 establishes that all feedstock b coming into ethanol plant j in period time t (qb^{IJ}_{bijmt}) plus the amount stored at the end of the previous time period (sb^{J}_{bjt-1}), should be equal to the amount of feedstock b used as raw material in ethanol plant j in period time t (w^{I-B}_{bjqt}) plus the amount that remains stored at the end of time period (sb^{J}_{bjt})

$$\sum_i \sum_m qb^{IJ}_{bijmt} + sb^{J}_{bjt-1} = \sum_q w^{I-B}_{bjqt} + sb^{J}_{bjt} \qquad \forall\ b,j,t \qquad (3)$$

The mass balances in ethanol plants establish the relationship between the inlet and outlet flows. In Eq. 4 μ^{P}_{bq} denotes the amount of biomass b required to produce ethanol with production technology q, and the mass balance coefficient used in Eq. 5 ($\mu^{B}_{E85,p'p''}$) represents the amount of E85 produced (from the mix of products p' and p'') in terms of the amount of product p' consumed, $w^{I-J}_{j,GAS,qt}$ represents the amount of gasoline used to produce ethanol in plant j with production technology q in time period t

$$w^{O-J}_{j,E85,qt} = \sum_b \mu^{P}_{bq} w^{I-B}_{bjqt} \qquad \forall\ j,q,t \qquad (4)$$

$$w^{O-J}_{j,E85,qt} = \mu^{B}_{E85,GAS,E100} w^{I-J}_{j,GAS,qt} \qquad \forall\ j,q,t \qquad (5)$$

In a similar way, the mass balance for gasoline is obtained through Eq. 6. The only difference is that we do not include storage terms, qp^{JK}_{jkmpt} represents the amount of gasoline transported from distribution center k to ethanol plant j by transportation mode m in time period t

$$\sum_k \sum_m qp^{JK}_{jkmpt} = \sum_q w^{I-J}_{jpqt} \qquad p=GAS, \forall\ j,t \qquad (6)$$

The inventory balance for the product (E85) is represented in Eq. 7, where the amount of E85 produced in plant j with production technology q in time period t (w^{O-J}_{jpqt}), plus the amount stored at the end of the previous time period must be equal to the amount transported from ethanol plant j to distribution center k, and other markets of ethanol consumption f by transportation mode m in time period t (qp^{JK}_{jkmpt} and qp^{JF}_{fjmpt}, respectively), plus the amount that remains stored at the end of time period t. Equation 8 shows the percentage of ethanol (β_j) devoted to the consumption of other industries

$$\sum_q w^{O-J}_{jpqt} + sp^{J}_{jpt-1} = \sum_k \sum_m qp^{JK}_{jkmpt} + \sum_k \sum_m qp^{JF}_{fjmpt} + sp^{J}_{jpt} \qquad p=E85,\ \forall\ j,t \qquad (7)$$

$$\sum_f \sum_m qp^{JF}_{fjmpt} = \beta_j w^{O-J}_{jpqt} \qquad p=E85,\ \forall\ j,t \qquad (8)$$

As it was stated in the previous section, we assume that the inventory level of product p (il^{EP}_{jpt}) is the minimum amount between replenishments required to provide markets with product p. It is defined in Eq. 9 as the ratio of the production flows of ethanol plants to the turnover ratio required for each ethanol plant j in each time period t, TOR^{J}_{jt}. This parameter indicates the number of times that the stock will be entirely replaced per time period (number of replenishments per time period). Equations 10 and 11 provide lower and upper bounds on the stored amount, based on the inventory level and based on the factors λ_{MAX} and λ_{MIN}

$$il^{EP}_{jpt} = \frac{\sum_m \left(\sum_k qp^{JK}_{jkmpt} + \sum_f qp^{JF}_{fjmpt} \right)}{TOR^{J}_{jt}} \qquad p=Eth,\ \forall\ j,t \qquad (9)$$

$$sp^{J}_{jpt} \le \lambda_{MAX} il^{EP}_{jpt} \qquad \forall\ j,p,t \qquad (10)$$

$$sp^{J}_{jpt} \ge \lambda_{MIN} il^{EP}_{jpt} \qquad \forall\ j,p,t \qquad (11)$$

The binary variable y^{J}_{jqst} represents whether or not the investment takes place for ethanol plant j with production technology q and size level s within time period t. Equations 12 and 13 set lower and upper bounds on the capacity of the new plants, represented by the variable npc^{J}_{jqst}

$$PC^{EP}_{jqs-1} y^{J}_{jqst} \le npc^{J}_{jqst} \le PC^{EP}_{jqs} y^{J}_{jqst} \qquad \forall\ j,p,s>1,t \qquad (12)$$

$$LBPC^{EP}_{jq} y^{J}_{jqst} \le npc^{J}_{jqst} \le PC^{EP}_{jqs} y^{J}_{jqst} \qquad \forall\ j,p,s=1,t \qquad (13)$$

The production of ethanol plants is limited by the existing capacity EPC^{J}_{jq} plus the capacity of the new plants built from period 1 to period t (Eqs. 14 and 15). A scalar between 0 and 1 (θ^{J}_{jq}) is used to denote the minimum percentage of production that is allowed in each plant j with production technology q

$$w^{O-J}_{jpqt} \ge \theta^{J}_{jq} \left(EPC^{J}_{jq} + \sum_{t' \le t} \sum_s npc^{J}_{jqst'} \right) \qquad p=Eth,\ \forall\ j,q,t \qquad (14)$$

$$w^{O-J}_{jpqt} \le EPC^{J}_{jq} + \sum_{t' \le t} \sum_s npc^{J}_{jqst'} \qquad p=Eth,\ \forall\ j,q,t \qquad (15)$$

Due to the limit on the availability of capital investment, an upper bound on the total number of new ethanol plants per year t and per potential region j is imposed in Eq. 16, taking into account all the technologies. A practical limit is the number of new ethanol plants depending on their production technology; i.e., the biochemical or thermochemical technologies have a larger upper bound than the hybrid one because the former are at a more advanced stage than the hybrid plants. This aspect is addressed in Eq. 17

$$\sum_q \sum_s y^{J}_{jqst} \le NJ^{TOT}_{jt} \qquad \forall\ j,t \qquad (16)$$

$$\sum_j y^{J}_{jqst} \le NJ_{qst} \qquad \forall\ q,s,t \qquad (17)$$

Gasoline distribution centers

The equations involved in this section are similar to those representing ethanol plants. Equation 18 is the inventory balance for gasoline, where the amount shipped from every refinery l by transportation mode m to distribution center k in time period t (qg^{LK}_{klmpt}), plus the amount of gasoline stored in distribution center k at the end of the previous time period, should be equal to the amount of gasoline that remains stored at the end of the time period t plus the gasoline sent to every ethanol plant j by transportation mode m in period t (qp^{JK}_{jkmpt}) plus the amount of gasoline mixed with every product p'' to produce product p' in period t ($w^{I-K}_{kp'pp''t}$)

$$\sum_m \sum_l qg^{LK}_{klmpt} + sp^K_{kpt-1} = \sum_q \sum_{p'} \sum_{p''} w^{I-K}_{kp'pp''t} + \sum_j \sum_m qp^{JK}_{jkmpt} + sp^K_{kpt} \qquad p = GAS, \ \forall \ k,t \quad (18)$$

In the same way, the amount of E85 delivered from every ethanol plant j to distribution center k by transportation mode m in period t (qp^{JK}_{jkmpt}) plus the amount of E85 stored in distribution center k at the end of the previous time period (sp^K_{kpt-1}) must be equal to the quantity of E85 mixed with each product p'' to produce any product p' ($w^{I-K}_{kp',E85,p''t}$) plus the amount of E85 that remains stored in distribution center k at the end of the time period t (sp^K_{kpt}) (Eq. 19)

$$\sum_j \sum_m qp^{JK}_{jkmpt} + sp^K_{kpt-1} = \sum_q \sum_{p'} \sum_{p''} w^{I-K}_{kp'pp''t} + sp^K_{kpt} \qquad p = E85, \ \forall \ k,t \quad (19)$$

The mass balance for products (Eq. 20), states that the amount of each product p produced in distribution center k in time period t (w^{O-K}_{kpt}) should be equal to the amount of product p delivered from distribution center k to all retail centers d by any transportation mode m in this time period t (qp^{KD}_{dkmpt})

$$w^{O-K}_{kpt} = \sum_d \sum_m qp^{KD}_{dkmpt} \quad \forall \ k,p,t \quad (20)$$

All fuel blends are obtained by mixing different amounts of gasoline and E85 according to the amount of ethanol required for the final blend. The mass balance coefficient for different products can be calculated based on densities of gasoline and E85 and the amount used of each blend. Therefore, the mass balance coefficient $\mu^{\mathrm{B}}_{pp'p''}$, relates the input of p' with the output of p, mixing p' and p'', as shown in Eq. 21

$$w^{O-K}_{kpt} = \sum_{p'} \sum_{p''} \mu^B_{pp'p''} w^{I-K}_{kpp'p''t} \quad \forall \ k,p,t \quad (21)$$

The definition of the inventory level in distribution centers is analogous to the definition of the inventory level in ethanol plants. The inventory level of product p that should be kept in each distribution center k in time period t (il^{DC}_{kpt}) is calculated with Eq. 22 with the turnover ratio of this distribution center k in time period t (TOR^K_{kt}), and the inlet flow of product p that is needed to produce every product p' in a mixture with any product p'' in distribution center k and time period t ($w^{I-K}_{p'pp''t}$).

$$il^{DC}_{kpt} = \frac{\sum_{p'} \sum_{p''} w^{I-K}_{kp'pp''t}}{TOR^K_{kt}} \qquad \forall \ k,p,t \quad (22)$$

The amount of product p stored in distribution center k in time period t is bounded by the average inventory level that is required to keep the necessary production. λ^K_{MAX} and λ^K_{MIN} are factors related to the desired availability of the storage

$$sp^K_{kpt} \le \lambda^K_{MAX} il^{DC}_{kpt} \qquad \forall \ k,p,t \quad (23)$$

$$sp^K_{kpt} \ge \lambda^K_{MIN} il^{DC}_{kpt} \qquad \forall \ k,p,t \quad (24)$$

The binary variable y^K_{kst} represents whether a distribution center k of size s is installed or not in time period t. The new capacity of distribution center k of size s in time period t (npc^K_{kst}) is bounded, according to Eqs. 25 and 26

$$PC^{DC}_{ks-1} y^K_{kst} \le npc^K_{kst} \le PC^{DC}_{ks} y^K_{kst} \quad \forall \ k, s>1, t \quad (25)$$

$$LBPC^{DC}_k y^K_{kst} \le npc^K_{kst} \le PC^{DC}_{ks} y^K_{kst} \quad \forall \ k, s=1, t \quad (26)$$

In Eq. 27 the production capacity of all products p produced in distribution center k within time period t (w^{O-K}_{kpt}) is limited by the capacity of the initial set of distribution centers, plus the capacity of those distribution centers installed before the current time period

$$\sum_p w^{O-K}_{kpt} \le EPC^K_k + \sum_s \sum_{t' \le t} npc^K_{kst'} \qquad \forall \ k,t \quad (27)$$

Finally, Eq. 28 limits the total number of distribution centers that can be installed in time period t and in potential location k (taking into account all the sizes considered in the model), and Eq. 29 limits the number of distribution centers of size s that can be installed in time period t

$$\sum_s y^K_{kst} \le NK^{TOT}_{kt} \quad \forall \ k,t \quad (28)$$

$$\sum_k y^K_{kst} \le NK_{st} \quad \forall \ s,t \quad (29)$$

As indicated in the problem statement, we first consider an aggregated model without gas station details and then a detailed model with gas stations details. The difference is in the retail centers formulation. Equations 1–29 are included in both the aggregated and detailed models. In the next subsection we describe the retail centers equations for the aggregated model, and in the following subsection we discuss retail centers formulation for the detailed model.

Retail centers—aggregated model.

Due to multiple inlet and outlet products of the retail centers and the combination of these inputs to produce any product, nonlinearities might arise in the mass balances. A disaggregation scheme is introduced to avoid these nonlinearities. Specifically, variable $w^{I-D}_{dpp'p''t}$ is defined to represent the amount of product p' mixed with product p'' to produce product p within retail center d in time period t. The mass balance for inlet products on retail centers is expressed in Eq. 30. It states that every product p that gets into a retail center d in time period t from any distribution center k and by any transportation mode m (qp^{KD}_{dkmpt}) plus the amount of product p that remains stored in retail center d since the end of the previous time period (sp^D_{dpt-1}) must be equal to the consumption of product p to produce every product p'' with a mix of product p' in retail center d in time period t ($wp^{I-D}_{dp'pp''t}$) plus the amount stored at the end of time period sp^D_{dpt}

$$\sum_k \sum_m qp^{KD}_{dkmpt} + sp^D_{dpt-1} = \sum_{p'} \sum_{p''} wp^{I-D}_{dp'pp''t} + sp^D_{dpt} \qquad \forall \ d,p,t \quad (30)$$

Equation 31 states that the amount of product p that is sold in retail center d in time period t (wp^{O-D}_{dpt}) must be equal to the sales

$$wp^{O-D}_{dpt} = sales_{dpt} \quad \forall \ d,p,t \quad (31)$$

The relationship between inputs and outputs is given by the mass balance coefficient ($\mu^B_{pp'p''}$) as it is shown in Eq. 32.

Table 2. Mass Balance Coefficient for Mixing Fuel Blends

	Raw Materials			
	GAS	E10	E85	Eth
E30	0.7	-	-	0.3
E30	-	0.7333	0.2667	-

This coefficient relates the amount of product p produced by mixing products p' and p''. Table 2 shows two examples: in the second line it can be noted that E30 can be obtained with 73.33% of E10 and 26.67% of E85 (volume). The numerical value for the coefficient $\mu^B_{E30,E10,E85}$ [kg E30/kg E10] is then obtained with the density of each blend

$$wp^{O-D}_{dpt} = \sum_{p'} \sum_{p''} \mu^B_{pp'p''} wp^{I-D}_{dpp'p''t} \quad \forall\ d,p,t \tag{32}$$

Equations 33–35 represent constraints on blend sales. The demand of higher ethanol blends can be satisfied with lower ethanol blends. In these equations, parameter DEM_{dt} refers to the demand of fuel (all ethanol and gasoline blends) in retail center d in time period t, and the parameter PB_p expresses what percentage of this demand corresponds to the demand of blend p.[29]

Equation 33 states that the summation of sales of every product p' that has a higher content of ethanol than blend p, should be less or equal than the summation of the demand of these fuel blends. Eq. 34 ensures that the sales of all fuel blends must be greater than these product demands. It is possible to relax this constraint because sales will increase to satisfy the demand, but a further increase would increase the objective function value, which is being minimized. Eq. 35 states that sales of E10 have to be greater or equal than E10 demand, because there is no other fuel blend that can satisfy its demand and also E10 can be used to satisfy the demand of other blends

$$\sum_{p' \geq p} sales_{dp't} \leq \sum_{p' \geq p} DEM_{dt} PB_{p'} \quad \forall\ d, p > E10, t \tag{33}$$

$$\sum_{p} sales_{dpt} \geq \sum_{p} DEM_{dt} PB_{p} \quad \forall\ d,t \tag{34}$$

$$sales_{dpt} \geq DEM_{dt} PB_p \quad \forall\ d, p{=}E10, t \tag{35}$$

We define the inventory level of product p in retail center d in time period t (il^{GS}_{dpt}) as the ratio between the amount of product p consumed in retail center d in this time period and the turnover ratio of retail center d in time period t (TOR^D_{dt}).

$$il^{GS}_{dpt} = \frac{\sum_{p'} \sum_{p''} wp^{I-D}_{dp'pp''t}}{TOR^D_{dt}} \quad \forall\ d,p,t \tag{36}$$

The inventory level of the retail centers is used to set bounds on the amount of product p stored, using λ^D_{MAX} and λ^D_{MIN} as factors related to the desired availability of the storage in Eqs. 37 and 38. Our model assumes values of one and three for these factors, respectively.

$$sp^D_{dpt} \leq \lambda^D_{MAX} il^{GS}_{dpt} \quad \forall\ d,p,t \tag{37}$$

$$sp^D_{dpt} \geq \lambda^D_{MIN} il^{GS}_{dpt} \quad \forall\ d,p,t \tag{38}$$

Retail centers — detailed model

The detailed model includes a description of gas stations in retail centers. In this model, each retail center represents a set of gas stations where the fuel is sold. To avoid the use of 0–1 variables for individual gas stations, we introduce integer variables to represent the number of gas stations of the same type, age and demand zone. The equations take into account the fact that gas stations have different designs according to the number of products they can produce (single or multiproduct). The variables $wp^{I-D}_{dp'pp''t}$ and wp^{O-D}_{dpt} indicate the flows of product consumed and produced, respectively. The equations corresponding to the aggregated model (mass balances; demand and inventory equations, Eqs. 30–38) are also included in the detailed formulation.

Every gas station has a lifetime τ_G, after which a retrofit must be performed to keep the gas station working. Otherwise, this gas station becomes inactive or idle. Figure 5 shows a scheme to describe the modeling of the aging of gas stations. The dashed line divides the figure into two main parts: the one above represents the active gas stations (all the circles, except the last row), and the one below represents the inactive gas stations (the last row of circles). The rows represent the age a of gas stations and the columns the year t in the time horizon.

In this way, the thick and continuous arrows at the very top of Figure 5 represent the new gas stations that are added to the set of active ones. The arrows that connect all the active gas stations of a time period t with the set of inactive gas stations in the same period of time (dotted arrows)

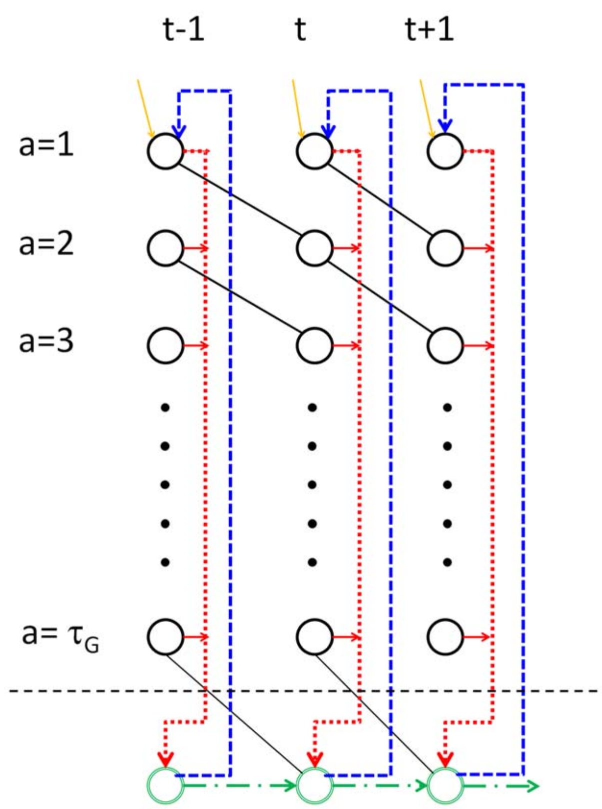

Figure 5. Modeling of gas stations.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

represent those gas stations that have been closed. The lines that connect the circle of age a and time period t with the circle of age $a+1$, and time period $t+1$ (continuous lines) represent the aging of the gas stations. The arrows that connect the set of inactive gas stations in year t with the circle in the very top in the same year (dashed arrows) represent the retrofit over inactive gas stations. Finally, the arrows that connect the set of inactive gas stations to each other throughout years (arrows of dots and dashes) represent the flow of gas stations that remain inactive from year $t-1$ to year t.

Equations 39 and 40 represent inventory balances for active gas stations (n_{dgta}) and idle gas stations (n^{I}_{dgt}), respectively. These groups can link to each other in the way that was explained above: closing an active gas station (n^{D}_{dgta}), performing a retrofit to an idle gas station (n^{R}_{dvt}) or just building a new one (n^{N}_{dgt}). Here n_{dgta} is the number of active gas stations of type g and age a within retail center d in time period t; n^{I}_{dgt} is the number of inactive gas stations of type g within retail center d in time period t; n^{D}_{dgta} is the number of dropped off gas stations of type g of age a within retail center d in time period t; n^{R}_{dvt} is the number of type v retrofits that take place within retail center d in time period t and n^{N}_{dgt} is the number of new gas stations of type g within retail center d in time period t. The initial set of gas stations is specified ($NINIT_{dga}$)

$$n_{dgta}=\left(NINIT_{dga-1}|_{t=1}+n_{dg,t-1,a-1}|_{t>1}\right)|_{a>1} + \left(\sum_{v\in GVO(g,v)} n^{R}_{dvt}+n^{N}_{dgt}\right)\Bigg|_{a=1} - n^{D}_{dgta} \quad \forall\ d,g,t,a \tag{39}$$

$$n^{I}_{dgt}=\sum_{a=\tau_G} NINIT_{dga}\Big|_{t=1}+n^{I}_{dgt-1}\Big|_{t>1}+\sum_{a} n^{D}_{dgta}+\sum_{a=\tau_G} n_{dgt-1a}\Big|_{t>1} - \sum_{v\in GVI(g,v)} n^{R}_{dvt} \quad \forall\ d,g,t \tag{40}$$

Other important constraints for the gas stations are those related to their capacity. The capacity is represented by both the storage capacity in the underground tanks and the capacity of delivering product p in each gas station. The capacity of the underground tanks in gas stations is determined through Eqs. 41 and 42. Lower and upper bounds are imposed. They are related to the number of active gas stations of type g and age a within retail center d in time period t (n_{dgta}), and to the use of a factor of maximum and minimum capacity of the underground tanks that store product p in type g gas stations within retail center d (SC^{MAX}_{dgp} and SC^{MIN}_{dgp}). These bounds may correspond to safety considerations[30] (Code of Federal Regulations 40 C.F.R Part 280). The subset $DPI(d,p)$ represents those products p that are input in retail center d

$$il^{GS}_{dpt} \le \sum_{a} \sum_{g\ \in\ GPI(g,p)} SC^{MAX}_{dgp} n_{dgta} \quad \forall\ d,p\in DPI(d,p),t \tag{41}$$

$$il^{GS}_{dpt} \ge \sum_{a} \sum_{g\ \in\ GPI(g,p)} SC^{MIN}_{dgp} n_{dgta} \quad \forall\ d,p\in DPI(d,p),t \tag{42}$$

The capacity to deliver product p in retail center d in time period t must be less than or equal to the total capacity of delivery of those gas stations that are able to produce product p. This fact is imposed by Eqs. 43–45. The variable c^{N}_{dgt} represents the equivalent quantity of gas stations of type g that are under construction in retail center d in time period t. This variable is subtracted in the capacity formula, because the gas stations under construction are not available to deliver fuel in the construction period. It is calculated in Eq. 46

$$w^{O-D}_{dpt} \le \sum_{g\ |\ GPO(g,p)} PC^{D}_{dg}\left[\left(\sum_{a} n_{dgta}\right)-c^{N}_{dgt}\right] \quad \forall\ d,p=\{E10;E30;E85\},t \tag{43}$$

$$w^{O-D}_{dpt}+w^{O-D}_{dp't} \le \sum_{g\ \left|\begin{smallmatrix}GPO(g,p)\\ GPO(g,p')\end{smallmatrix}\right.} PC^{D}_{dg}\left[\left(\sum_{a} n_{dgta}\right)-c^{N}_{dgt}\right] \quad \forall\ d,\{p,p'\}=\{\{E10,E30\};\{E10,E85\};\{E30,E85\}\},t \tag{44}$$

$$w^{O-D}_{d,E10,t}+w^{O-D}_{d,E30,t}+w^{O-D}_{d,E85,t} \le \sum_{g\ \left|\begin{smallmatrix}GPO(g,E10)\\ GPO(g,E30)\\ GPO(g,E85)\end{smallmatrix}\right.} PC^{D}_{dg}\left[\left(\sum_{a} n_{dgta}\right)-c^{N}_{dgt}\right] \quad \forall\ d,t \tag{45}$$

$$c^{N}_{dgt}=\left(\sum_{v\in GVO(g,v)} PTO^{V}_{dvt} n^{R}_{dvt}\right)-\left(PTO^{G}_{dgt} n^{N}_{dgt}\right) \quad \forall\ d,g,t \tag{46}$$

The factor PTO^{G}_{dgt} represents the percentage of the time period t during which a gas station of type g within retail center d is being built (from new). In a similar way PTO^{V}_{dvt} can be defined for the retrofitted gas stations. With these factors we define the capacity under construction of type g within retail center d in time period t.

If a gas station exists, it must deliver at least a minimum amount of fuel. To take this fact into account, a lower bound on the amount of fuel delivered is imposed in Eqs. 47 and 48

$$w^{I-D}_{dpppt} \ge 0.50\ PC^{D}_{dg} \sum_{a} n_{dgta} \quad \forall\ d,\{p,g\}=\{\{E10,G1\};\{E30,G2\}\},t \tag{47}$$

$$w^{I-D}_{d,E10,E10,E85,t}+w^{I-D}_{d,E30,E10,E85,t}+w^{I-D}_{d,E85,E10,E85,t} \ge 0.50\ PC^{D}_{d,G3} \sum_{a} n_{d,G3,ta} \quad \forall\ d,t \tag{48}$$

Objective function

The investment cost for the different stages of the supply chain is calculated with Eqs. 49–53 as follows

$$c^{INV}=\sum_{t}\left[\sum_{i} tic^{HS}_{it}+\sum_{j} tic^{EP}_{jt}+\sum_{k} tic^{DC}_{kt}+\sum_{d} tic^{GS}_{dt}\right] \tag{49}$$

$$tic^{HS}_{it}=\sum_{b}\left(FIC^{HS}_{i}\ y^{I}_{bit}+VIC^{HS}_{i}\ bhs_{bit}\right) \quad \forall\ i,t \tag{50}$$

$$tic^{GS}_{dt}=\sum_{v} FCR_{dv}\ n^{R}_{dvt}+\sum_{g} FCN_{dg}\ n^{N}_{dgt} \quad \forall\ d,t \tag{51}$$

$$tic^{EP}_{jt} = \sum_q \sum_s \left[FIC^{EP}_{jqs-1}\; y^J_{jqst} + \left(npc^J_{jqst} - PC^{EP}_{jqs-1} y^J_{jqst}\right) \frac{FIC^{EP}_{jqs} - FIC^{EP}_{jqs-1}}{PC^{EP}_{jqs} - PC^{EP}_{jqs-1}}\right] \quad \forall\ j,t \tag{52}$$

$$tic^{DC}_{kt} = \sum_s \left[FIC^{DC}_{ks-1}\; y^K_{kst} + \left(npc^K_{kst} - PC^{DC}_{ks-1} y^K_{kst}\right) \frac{FIC^{DC}_{ks} - FIC^{DC}_{ks-1}}{PC^{DC}_{ks} - PC^{DC}_{ks-1}}\right] \quad \forall\ k,t \tag{53}$$

For the investment cost in harvesting sites, defined in Eq. 50, fixed and variable cost coefficients are used. For the investment in gas stations, defined in Eq. 51, two fixed costs are used, corresponding to retrofits of gas stations (FCR_{dv}) or construction of new ones (FCN_{dg}). No variable cost is included because only one size is considered in investments on gas stations. For the remaining investment costs, defined in Eqs. 52 and 53, the variable cost coefficients are implicitly involved.[20,31]

The processing and maintenance cost is also calculated with a variable and a fixed cost for each industry involved in the supply chain (Eq. 54)[20]

$$\begin{aligned} c^{PR} = \sum_t \Bigg[& \sum_i \left(\alpha^{HS}_{it}\, tic^{HS}_{it} + \sum_b VPC^I_{bit} bhs_{bit}\right) \\ & + \sum_j \left(\alpha^{EP}_{jt}\, tic^{EP}_{jt} + \sum_p \sum_q VPC^J_{jqt} w^{O-J}_{jpqt}\right) \\ & + \sum_k \left(\alpha^{DC}_{kt}\, tic^{DC}_{kt} + \sum_p \sum_q VPC^K_{kt} w^{O-K}_{kpt}\right) \\ & + \sum_d \left(\alpha^{GS}_{dt}\, tic^{GS}_{dt} + \sum_d \sum_p VPC^D_{dpt} w^{O-D}_{dpt}\right) \Bigg] \end{aligned} \tag{54}$$

The cost of transportation in Eq. 55 is calculated as the summation of fixed and variable costs (regarding distance) over all the possible connections in the supply chain by all the feasible transportation modes and in all-time periods[20]

$$\begin{aligned} c^{TR} = \sum_t \sum_m \Bigg[& \sum_b \sum_i \sum_j \left(FTC^B_{bmt} + VTC^B_{bmt} D^{IJ}_{ijm}\right) qb^{IJ}_{bijmt} \\ & + \sum_p \sum_j \sum_k \left(FTC^P_{pmt} + VTC^P_{pmt} D^{JK}_{jkm}\right) qp^{JK}_{jkmpt} \\ & + \sum_p \sum_j \sum_f \left(FTC^P_{pmt} + VTC^P_{pmt} D^{FJ}_{fjm}\right) qp^{JF}_{fjmpt} \\ & + \sum_p \sum_k \sum_l \left(FTC^P_{pmt} + VTC^P_{pmt} D^{KL}_{klm}\right) qg^{LK}_{klmpt} \\ & + \sum_p \sum_d \sum_k \left(FTC^P_{pmt} + VTC^P_{pmt} D^{DK}_{dkm}\right) qp^{KD}_{dkmpt} \Bigg] \end{aligned} \tag{55}$$

Finally, storage cost is computed from Eq. 56. Equation 57 calculates the purchase cost of the gasoline required to perform the blending (we use the wholesale price)

$$\begin{aligned} c^{ST} = \sum_t \Bigg[& \sum_b \sum_j SC^{BJ}_{bjt}\; sb^J_{bjt} + \sum_j \sum_p SC^{PJ}_{jpt}\; sp^J_{jpt} \\ & + \sum_k \sum_p SC^{PK}_{kpt}\; sp^K_{kpt} + \sum_d \sum_p SC^{PD}_{dpt}\; sp^D_{dpt} \Bigg] \end{aligned} \tag{56}$$

$$c^{PU} = \sum_k \sum_l \sum_m \sum_p \sum_t CG_{it} qg^{LK}_{klmpt} \tag{57}$$

The objective function is calculated as the summation over the previously described costs, as shown in Eq. 58. Data on the objective function parameters are available from the authors upon request.

$$\min c = c^{INV} + c^{PR} + c^{TR} + c^{ST} + c^{PU} \tag{58}$$

Examples

We have formulated two models as stated in the Problem Statement section. The first one is an aggregated model that is described by Eqs. 1–38 and 49–58 in which the retail center formulation has no details about how the fuel is distributed to customers. However, the second one is a detailed model described by Eqs. 1–58, in which the retail center formulation includes information about gas stations in each region.

The time horizon for both problems is 20 years with periods of 4 months for the first 10 years, and periods of 6 months for the next 10 years, requiring a total of 50 time periods. Each retail center represents one county of the state of Alabama. The fuel demand is estimated based on the population of each county and the gasoline consumption of the entire county.[32] Figure 6 shows total fuel demand profile for Alabama state over a 20 year time horizon. We consider that the normal growth of the number of cars throughout the time is reflected in an initial increase of demand, but in the middle term this effect is roughly balanced with the increase of engine efficiency. However, the decrease at the end of the time horizon is due to a further increase of energy efficiency and/or the possibility to use another energy source for transportation.

Figure 7 shows the nodes in the potential supply chain. The shadowed region (AL state) represents the place where one retail center per county is considered. The profile of the demand for E10, E30 and E85 is shown in Tables 3 and 4. Table 3 shows the total demand of fuel estimated by the gasoline consumption per year per capita reported in US 2000 census.[24]

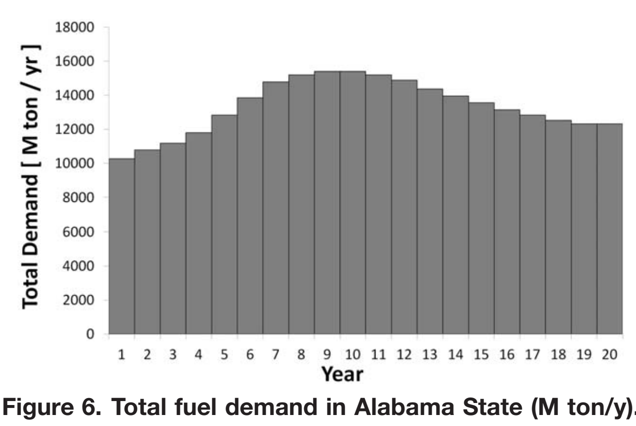

Figure 6. Total fuel demand in Alabama State (M ton/y).

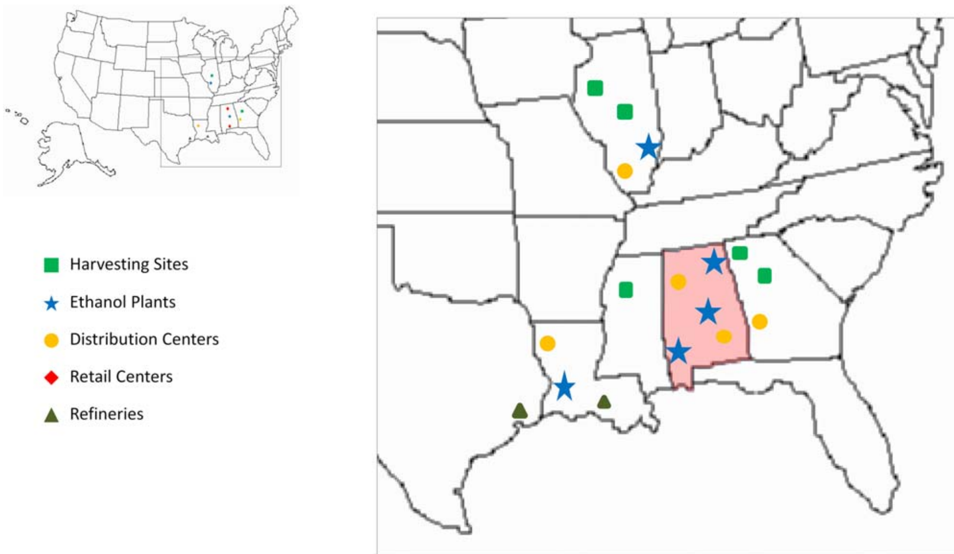

Figure 7. Potential locations for the nodes of the supply chain.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 3. Total Demand of Fuel in the First Year of the Time Horizon

County	Gasoline Consumption [ton/yr] (2005)	County	Gasoline Consumption [ton/yr] (2005)	County	Gasoline Consumption [ton/yr] (2005)
Autaga	90,136	Dallas	72,378	Marengo	34,731
Baldwin	301,050	DeKalb	117,452	Marion	50,833
Barbour	45,351	Elmore	130,986	Marshall	153,641
Bibb	37,849	Escambia	63,292	Mobile	682,145
Blount	94,680	Etowah	172,489	Monroe	38,102
Bullock	18,027	Fayette	28,477	Montgomery	378,843
Butler	34,598	Franklin	52,366	Morgan	197,364
Calhoun	195,847	Geneva	44,249	Perry	17,493
Chambers	56,513	Greene	14,940	Pickens	32,615
Cherokee	42,926	Hale	26,031	Pike	54,340
Chilton	72,086	Henry	28,578	Randolph	37,846
Choctaw	22,891	Houston	167,727	Rusell	87,453
Clarke	42,669	Jackson	87,916	St.Clair	138,072
Clay	23,012	Jefferson	1,087,599	Shelby	322,225
Cleburne	24,729	Lamar	24,056	Sumter	22,733
Coffee	82,500	Lauderdale	153,129	Talladega	135,921
Colbert	89,900	Lawrence	56,718	Tallapoosa	68,738
Conecuh	21,849	Lee	231,648	Tuscaloosa	321,516
Coosa	19,059	Limestone	136,732	Walker	110,703
Covington	62,377	Lowndes	18,663	Washington	29,039
Crenshaw	22,969	Macon	35,433	Wilcox	19,276
Cullman	132,808	Madison	553,013	Winston	40,441
Dale	83,000				

Table 4. Percentage of the Total Demand for each Blend

Year Blend	1–2	3–5	6–10	11–15	16–20
E10	80	68	50	35	22
E30	15	25	35	40	43
E85	5	7	15	25	35

Table 5. Yields Associated to the Different Ethanol Technologies (Ton Ethanol/Ton Biomass)

	Switchgrass	Wood Chips
Biochemical	0.28	0.17
Thermochemical	0.20	0.19
Hybrid	0.33	0.26

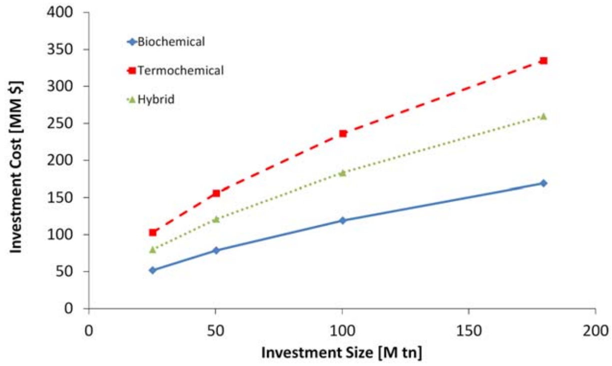

Figure 8. Investment on different ethanol technologies.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The estimations shown in Table 3 correspond to the first year of the time horizon, for each county. In the subsequent years, the demand is increased. While in the last year of the time horizon the demand is 20% higher than the value in the first year, in the middle term it has a peak of 50% of the value in the first year. Table 4 shows the percentage of the total demand that corresponds to each fuel blend.

The main data are shown in Table 5 and Figure 8. Table 5 shows the yield of ethanol from biomass.[5,33] Figure 8 shows data for investment size and cost[5] and the projection with the six tenth rule.

In the following section, one example is solved with both models, with CPLEX12.4 in GAMS.[34]

Aggregated model example

This example is solved for the state of Alabama with the 67 counties shown in Table 3. We consider five harvesting sites with 2 raw materials (wood chips and switchgrass), 5 ethanol plants, with 3 feasible production technologies, 2 petroleum refineries, 5 distribution centers, and 67 retail centers (one for each AL county). The results can be summarized as follows. As shown in Figure 9, three out of five potential locations for harvesting sites are selected. In these harvesting sites, switchgrass is sown. The optimal solution includes investment in three potential locations for ethanol plants according to Table 6 (Carmi, Scottsboro and Montgomery). It can be noted that the preferred technology is the hybrid one, combining biomass gasification and synthesis gas fermentation: 15 out of 24 new ethanol plants are hybrid. The location of these ethanol plants are shown with stars in Figure 9.

Table 6. Ethanol Plants Built over 20 Year Time Horizon

Carmi[IL]	Number of Plants/Capacity [M ton/yr]		
Year	Biochemical	Thermochemical	Hybrid
1	2/280	1/180	
6			3/540
TOTAL	2/280	1/180	3/540
Scottsboro [AL]	**Number of Plants/Capacity [M ton/yr]**		
Year	Biochemical	Thermochemical	Hybrid
1	2/330	1/180	2/350
4			3/510
9			1/180
11			3/460
TOTAL	2/330	1/180	9/1,500
Montgomery [AL]	**Number of Plants/Capacity [M ton/yr]**		
Year	Biochemical	Thermochemical	Hybrid
1	2/265.8	1/180	
11			3/460
TOTAL	2/265.8	1/180	3/460

Figure 10 shows the integrated supply chain for fuel distribution to the retail centers in the state of Alabama. It can be seen that the distribution center located in the state of Louisiana (LA2) provides the southwest of Alabama with fuel (first map), and the distribution center located in the state of Georgia (GA3) provides fuel to the east of Alabama State (last map). The rest of retail centers in this state are supplied by distribution centers within the same state (the distribution center AL4 provides the region in the second map, and AL5 provides the region in the third map).

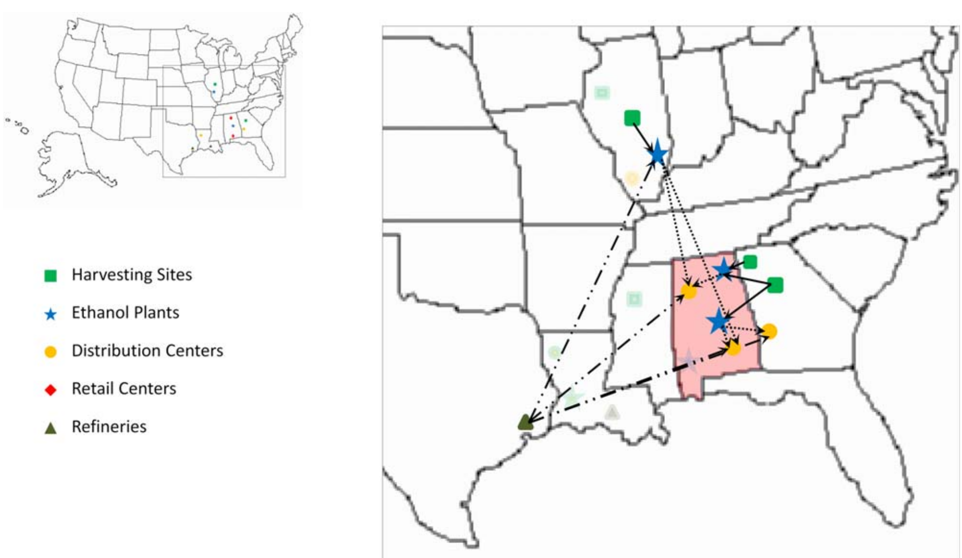

Figure 9. Optimal locations for the nodes of the supply chain.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

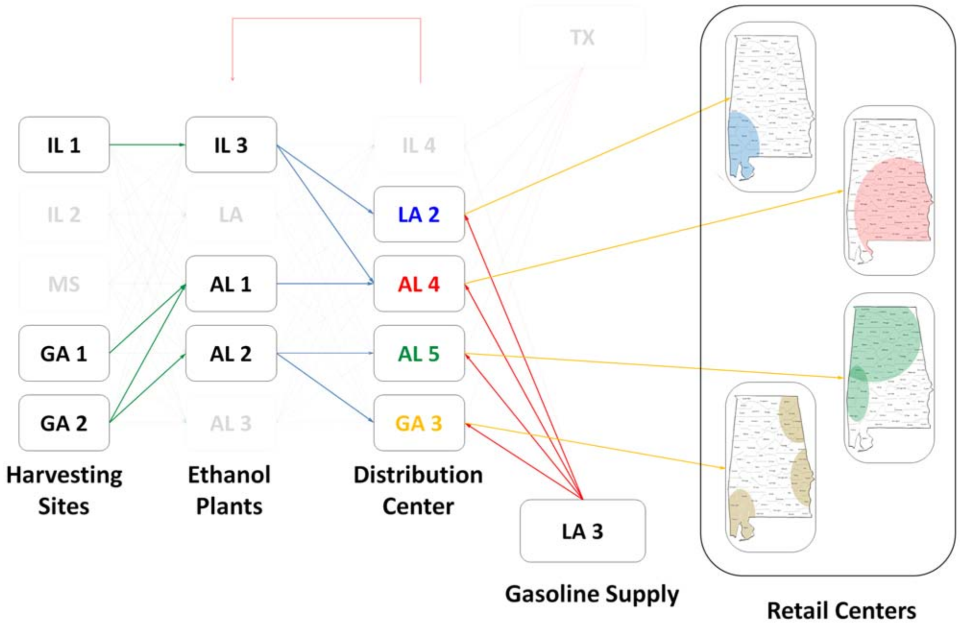

Figure 10. Optimal connections between the nodes of the supply chain.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The price of fuels with higher content of ethanol is lower than the retail price of fuels with lower content of ethanol. For that reason, we consider a lower production cost for blends with higher ethanol content. We have also considered blending pumps costs associated with the commercialization of E85 in retail centers. Because of that and because of the entire cost of blends, Figure 11 shows that sales are as follows: the demand of E10 is fully satisfied with E10 blend; sales of E85 satisfy only 50% of its demand, and the demand is fully satisfied with lower ethanol blends. Sales of E30 at the beginning of the time horizon are at the minimum level too (50% of the demand). However, throughout the time horizon, sales of E30 increase with respect to its demand in order to partially satisfy the E85 demand. In summary, ethanol consumption increases as compared to gasoline consumption to meet the demand.

The computational results are shown in Table 7, where it can be seen that the model was solved in about 5 min CPU time with an optimality gap of less than 1%.

Detailed model example

This example is solved, as the previous one, for 5 harvesting sites with 2 raw materials (wood chips and switchgrass), 5 ethanol plants with 3 feasible production technologies, 2

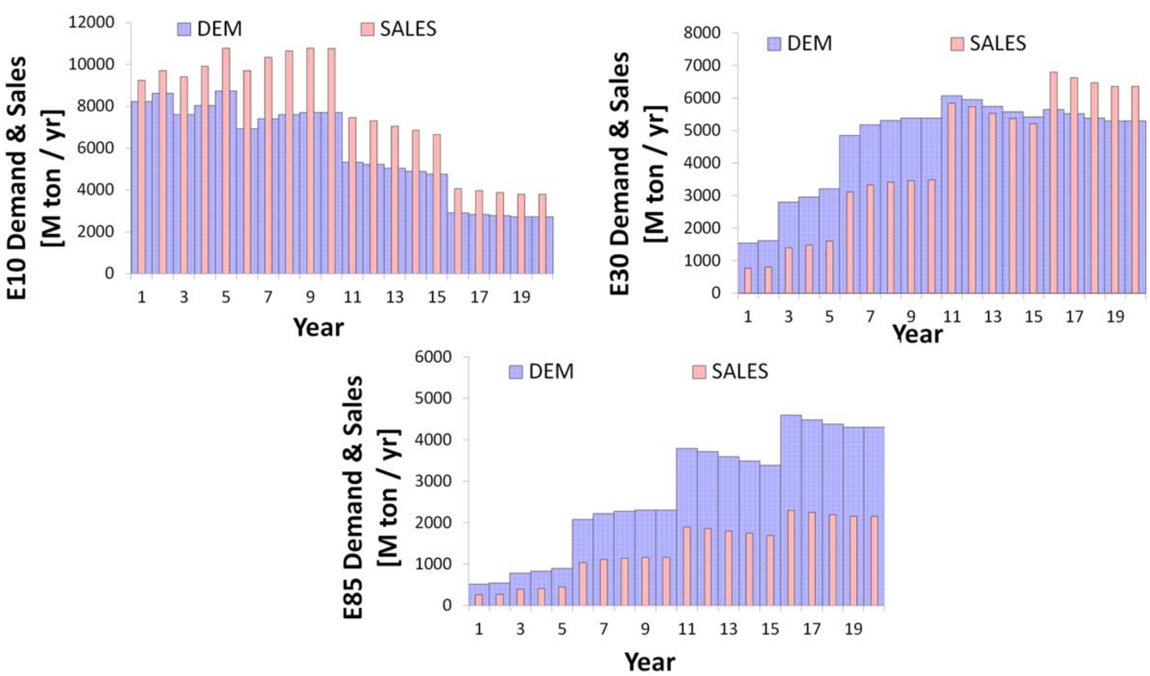

Figure 11. Demand and sales of fuel blends in Alabama State (M ton/y).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 7. Computational Results for Aggregated Model

Solver	CPLEX 12.4
Equations	109,363
Variables	136,223
Discrete Variables	1,400
Total Cost [MM USD]	140,282.7
Solution Time [sec]	332.5
Gap [%]	0.5329

Processor: Intel Core i7–2640M 2.80GHz - 8GB RAM

petroleum refineries and 5 distribution centers. We consider 67 retail centers (one for each Alabama County), and we consider the number of different types of existing gas stations for each one of them. The time horizon is 20 years.

As we described in the problem statement, the difference between the aggregated and the detailed model is in the retail center formulation. Additional data for the detailed model include the initial number of gas stations in each county of Alabama state. The information on the number of gas stations in each county is obtained from 2002 Economic Census[24] and has been updated to 2012 as a linear function of population growth. We have indicated the total number of gas stations according to their age. Table 8 shows the initial number of gas stations for some counties as an example.

The results obtained in the detailed model are similar to those obtained with the aggregated one (see previous section). However, it is worth to point out that this model provides the change in the number of gas stations involved in the supply chain as a function of time. Figure 12 shows the time profile of number and type of gas stations throughout the 20 year time horizon. While in the first years the number of G1 gas stations remains almost constant, the major change occurs in the middle part of the time horizon, when the number of G1 gas stations decreases. By this time the number of G2 and G3 gas stations increases, mainly due to retrofits on G1 gas stations.

The information displayed in Figure 12 can be useful to obtain an investment plan over gas stations in order to satisfy the predicted demand of blends and choose a suitable location for each gasoline station.[35] Even though this plan does not contain information about which gas station may be

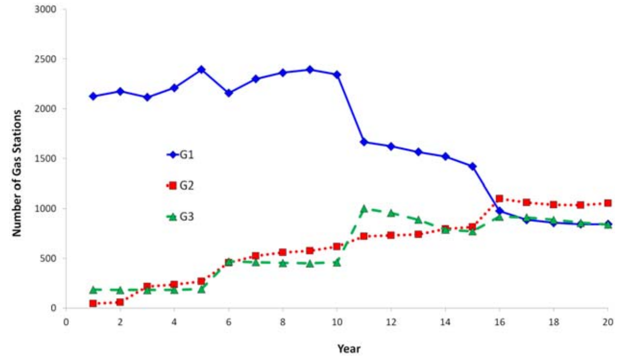

Figure 12. Time profile of total number of gas stations in Alabama State.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

subjected to retrofit, it provides information about the number of gas stations that should be retrofitted within each county considered in the model.

The gas stations that have blending pumps can in principle provide any product. Therefore, each G3 gas station can sell any blend. As an example, we include two figures with results obtained for Jefferson and Monroe counties. Figure 13 shows total demand and sales of each blend in G3 gas stations from Jefferson County throughout the 20 year time horizon. Most of the E10 demand is satisfied with G1 gas stations, while G3 gas stations provide only 25% of the demand. Almost all E30 demand is satisfied with multiproduct gas stations (G3). It can be concluded that new multiproduct gas stations are not selected to provide the market with E10 (because the infrastructure for this blend is already developed). Regarding E85 sales, only 50% of total demand is produced; the amount of demand which is not satisfied with this blend is mostly satisfied with E10. On the other hand, given that the demand of fuel in the near future will be composed by several blends, it is more convenient to install multiproduct gas stations instead of single-product gas stations for different blends.

Figure 14 shows the time profile for the production of each blend in multiproduct gas stations within Monroe

Table 8. Initial Number of Gas Stations in Alabama State (Detail of Four Counties)

Type	Age										
	1	2	3	4	5	6	7	8	9	10	TOT
	Autaga county										
Gl (E10)	4	7	1	5	1	5	2	1	4	4	34
G2 (E30)	1			1		1	1				4
G3 (All)	1				1						2
	Baldwin county										
Gl (E10)	2	11	11	25	22	22	22		5	12	132
G2 (E30)	1		2	3	2			3	2	3	16
G3 (All)	4	1	2	1							8
	Monroe county										
Gl (E10)	1	2	2	3		1	1		2	1	13
G2 (E30)		1			1						2
G3 (All)	1										1
	Talladega county										
Gl (E10)	1	7	3	8	2	8	2	3	9	9	52
G2 (E30)	1			1		1	1			1	5
G3 (All)	1		2								3
	ALABAMA STATE										
G1 (E10)	323	263	280	268	304	276	294	218	217	276	2,719
G2 (E30)	26	31	40	41	32	26	37	32	29	21	315
G3 (All)	48	34	31	16	5						134

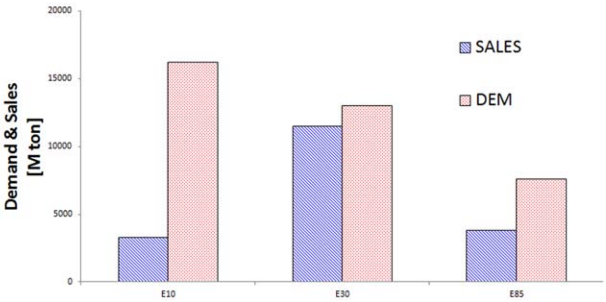

Figure 13. Demand and sales in multiproduct gas stations within Jefferson County.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

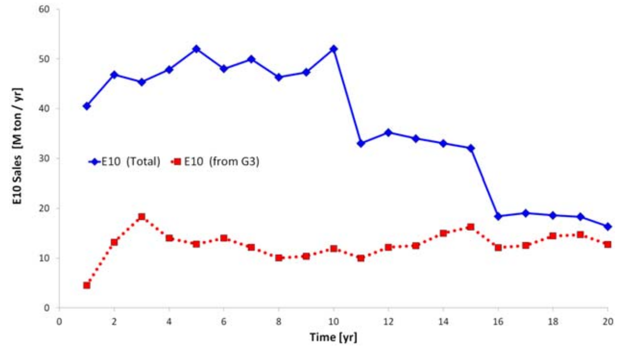

Figure 15. Time profile for E10 total sales and sales of E10 in multiproduct gas stations (G3) within Monroe County.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

County, throughout the 20 year time horizon. We can conclude that the production of E30 and E85 in multiproduct gas stations (G3) within Monroe county increases with time and the production of E10 decrease with time. Throughout the time horizon, the number of G1 gas stations is reduced (see Figure 12). Then, most of E10 consumed is provided by G3 gas stations (see Figure 15).

In this model, which considers integer variables for gas stations in each one of the 67 AL counties, and taking into account an initial set of almost 3,200 gas stations, it becomes a challenge to obtain a solution within reasonable time. As shown in Table 9, the solution time for this MILP problem is more than 3 h to reach an optimality gap of 1%.

We can note that the difference in the objective function between the aggregated and the detailed model is due to the cost of the gas stations. In the detailed model, we take into account costs on gas stations that are not considered in the aggregated model, such as investment costs in the new and retrofitted gas stations, as well as transportation costs to the specific locations, which make an overall increase in the total cost of 18%.

On the other hand, the number of discrete variables in the detailed model is 97,880. However, since some integer variables (n_{dgta} and $n^{I}{}_{dgt}$) are calculated with an equation that involves only integer variables and integer coefficients, they can be defined as continuous variables. Therefore, the number of discrete variables is reduced to 53,660, which is still much larger than the 1,400 discrete variables in the aggregated model. Since the computational time is quite large (11,856 CPUs), this motivates the use of a bilevel decomposition method that is described in the supplementary material. In this scheme the problem is decomposed into an upper level problem that makes the decisions on the selection of major nodes in the supply chain, and into a lower level problem that is concerned with the detailed retrofit design of the gas stations. The proposed bilevel decomposition reduces the computational time to 7,137 CPUs, yielding a computational saving of about 40%.

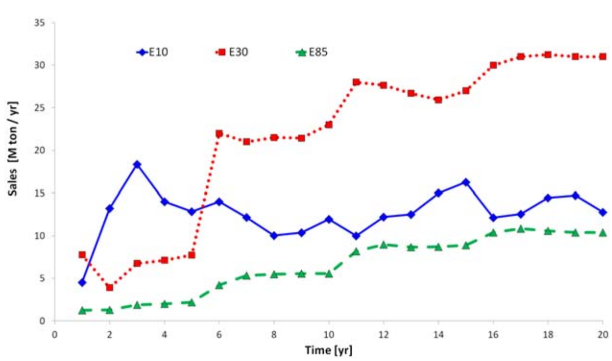

Figure 14. Time profile for the sales of multiproduct gas stations (G3) within Monroe County.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

We can conclude that numerical results obtained with the aggregated model, which is an approximation of the detailed one, have no impact in defining the overall structure of the supply chain. Considering more detail at the retail centers level does not change the upstream results obtained (at harvesting sites, ethanol plants and distribution centers level). However, the overall cost of the supply chain is underestimated in the aggregated model, as investment costs for the new gas stations and transportation costs to the specific gas stations are not taken into account, which justifies the development of the detailed model.

Conclusions

In this work, we have proposed an MILP model for the gasoline and ethanol supply chain, including from harvesting sites to retail centers. Different levels of detail are included within a superstructure. We have formulated two models, an aggregated one that considers the fuel demand per county, and a detailed model that also considers the number of gas stations needed to satisfy the fuel demand in each county. Gas stations details are considered within retail centers formulation. In the latter model, the need for retrofit projects, blending pumps and new gas stations are optimization decisions. Five potential locations and three ethanol technologies

Table 9. Computational Results for Detailed Model

Solver	CPLEX 12.4
Equations	211,875
Variables	240,745
Discrete Variables	53,660
Total Cost [MM USD]	165,414.2
Solution Time [sec]	11,856.2
Gap [%]	1.00

Processor: Intel Core i7–2640M 2.80GHz - 8GB RAM are included for ethanol plants: biochemical, thermochemical and hybrid. Numerical results show that the hybrid process is as competitive as the biochemical and thermochemical processes (larger yield and higher costs). Distribution centers receive pure ethanol and/or E85 from ethanol plants and gasoline from refineries, and they are able to produce any required blend. For simplicity, this article takes into account only E10, E30 and E85, but the model can be easily extended to any other set of fuel blends.

We have considered different types of gas stations: those that can commercialize only one type of blend and those that can commercialize any blend, with the use of blender pumps. Future trends predicted by the model indicate that single blend gas stations will be replaced by multiple blend gas stations, with blender pumps. Optimal results indicate that most gas stations work during their entire lifetime (10 years) before any retrofit is carried out. However, at the beginning of the time horizon, many gas stations that can only provide E10 to the market are retrofitted to provide multiple blends to the market with the addition of a blender pump.

Finally, we have proposed a bilevel decomposition algorithm (see online for Supplementary Material) which first solves a strategic planning model that takes more general decisions and iteratively uses this solution to bound a more detailed model. The computational time is reduced by almost 40%.

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Notation

Sets

A = age of gas station
B = biomass feedstock
D = demand zones, gas stations
F = alternative ethanol markets
G = type of gas stations
I = harvesting sites
J = ethanol plants
K = gasoline distribution centers
L = gasoline supply
M = transportation modes
P = products
Q = technologies
S = capacity levels
T = time periods
TY = years
V = retrofit mode
$DPI\ (d,p)$ = if product p is an input of retail center d
$DPO\ (d,p)$ = if product p is an output of retail center d
$GPI\ (g,p)$ = if product p is an input of type g gas station
$GPO\ (g,p)$ = if product p is an output of type g gas station
$GVI\ (g,v)$ = if a retrofit type v is done over a type g gas station
$GVO\ (g,v)$ = if a retrofit type v generates a type g gas station

Variables

bhs_{bit} = biomass b available in harvesting site i in time period t, ton B/per
c = total cost, \$
c^{INV} = total investment cost, \$
c^{N}_{dgt} = gas stations of type g under construction in retail center d in time period t, GS/per
c^{PR} = operation and maintenance cost, \$
c^{PU} = gasoline purchase cost, \$
c^{ST} = storage cost, \$
c^{TR} = transportation cost, \$
il^{DC}_{kpt} = inventory level of product p kept in distribution center k in time period t, ton P/repl
il^{EP}_{jpt} = inventory level of product p kept in ethanol plant j in time period t, ton P/repl
il^{GS}_{dpt} = inventory level of product p kept in gas station d in time period t ton, P/repl
n_{dgta} = no. of active type g gas stations with age a in retail center d in time period t, GS/per
n^{ref}_{dgt} = no. of active type g gas stations in retail center d in time period t for reformulated model, GS/per
n^{D}_{dgta} = number of dropped-off type g gas stations with age a in retail center d in time period t, GS/per
$n^{D,ref}_{dgt}$ = number of dropped-off type g gas stations in retail center d in time period t for reformulated model, GS/per
n^{I}_{dgt} = number of idle type g gas stations in retail center d in time period t, GS/per
n^{N}_{dgt} = number of new type g gas stations in retail center d in time period t, GS/per
n^{R}_{dvt} = number of type v retrofitted gas stations in retail center d in time period t, GS/per
npc^{J}_{jqst} = new production capacity of ethanol plant j with production technology q of size s in period time t, ton Eth/per
npc^{K}_{kst} = new production capacity of gasoline distribution center k of size s in period time t, ton blend/per
qb^{IJ}_{bijmt} = flow of biomass b from harvesting site i to ethanol plant j by transportation mode m in time period t, ton B/per
qg^{LK}_{klmpt} = flow of gasoline from refinery l to distribution center k by transportation mode m in time period t, ton G/per
qp^{JF}_{fjmpt} = flow of product p from ethanol plant j to alternative ethanol markets f by transportation mode m in time period t, ton P/per
qp^{JK}_{jkmpt} = flow of product p from ethanol plant j to distribution center k by transportation mode m in time period t, ton P/per
qp^{KD}_{dkmpt} = flow of product p from distribution center k to retail center d by transportation mode m in time period t, ton P/per
$sales_{dpt}$ = sales of product p within retail center d in time period t, ton P/per
sb^{J}_{bjt} = storage of biomass b in ethanol plant j in time period t, ton B/per
sp^{D}_{dpt} = storage of product p in retail center d in time period t, ton P/per
sp^{J}_{jpt} = storage of product p in ethanol plant j in time period t, ton P/per
sp^{K}_{kpt} = storage of product p in distribution center k in time period t, ton P/per
tic^{DC}_{kt} = total capital investment cost in distribution center k in time period t, \$
tic^{EP}_{jt} = total capital investment cost in ethanol plant j in time period t, \$
tic^{GS}_{dt} = total capital investment cost within retail center d in time period t, \$
tic^{HS}_{it} = total capital investment cost in harvesting site i in time period t, \$
w^{J-B}_{bjqt} = amount of biomass b consumed in ethanol plant j of production technology q within time period t, ton B/per
$w^{J-D}_{dpp'p''t}$ = amount of product p' mixed with product p'' to produce product p within retail center d in time period t ton P′/per
w^{J-J}_{jpqt} = amount of product p consumed in ethanol plant j of production technology q within time period t, ton P/per
$w^{J-K}_{kpp'p''qt}$ = amount of product p' mixed with product p'' to produce product p in distribution center k in time period t, ton P′/per
w^{O-D}_{dpt} = amount of product p produced in retail center d in time period t, ton P/per
w^{O-J}_{jpqt} = amount of product p produced in ethanol plant j with production technology q in time period t, ton P/per
w^{O-K}_{kpt} = amount of product p produced in distribution center k in time period t ton P/per
y^{I}_{bit} = whether biomass b is sown in harvesting site i in time period t or not
y^{I-MP}_{bi} = whether biomass b is sown in harvesting site i or not for MP model
y^{J}_{jqst} = whether ethanol plant j with production technology q and size s is installed in time period t or not

y_{jq}^{J-MP} = whether ethanol plant j with production technology q is installed or not for MP model
y_{kst}^{K} = whether distribution center k of size s is installed in time period t or not
y_{k}^{K-MP} = whether distribution center k is installed or not for MP model

Parameters

α_{kt}^{DC} = fixed production cost in distribution center k in time period t as a percentage of investments, %
α_{jt}^{EP} = fixed production cost in ethanol plant j in time period t as a percentage of investments, %
α_{dt}^{GS} = fixed production cost in retail center k in time period t as a percentage of investments, %
α_{it}^{HS} = fixed production cost in harvesting sites i in time period t as a percentage of investments, %
β_j = percentage of ethanol in ethanol plant j destinated to consumption of other industries, %
λ_{MAX} = factor to estimate the maximal storage capacity to handle the needed inventory, %
λ_{MIN} = factor to estimate the minimal storage capacity required to handle the needed inventory, %
$\mu_{pp'p''}^{B}$ = amount of product p' needed to produce p in a mix with p'', ton P/ton P$'$
μ_{bq}^{P} = yield of ethanol to biomass b associated with production technology q, ton E100/ton B
θ_{jq}^{J} = minimal percentage of production allowed in ethanol plant j with production technology q, %
AB_{bit} = amount of available biomass b in harvesting site i in time period t ton B/per
CG_{lt} = cost of gasoline in refinery l in time period t, \$/ton G
D_{dkm}^{DK} = distance between distribution center k and retail center d by transportation mode m, km
D_{fjm}^{FJ} = distance between ethanol plant j and alternative market f by transportation mode m, km
D_{ijm}^{IJ} = distance between harvesting site i and ethanol plant j by transportation mode m, km
D_{jkm}^{JK} = distance between ethanol plant j and distribution center k by transportation mode m, km
D_{klm}^{KL} = distance between refinery l and distribution center k by transportation mode m, km
DEM_{dt} = demand of fuel in retail center d in time period t, ton/per
EPC_{jq}^{J} = existing production capacity of ethanol plant j with production technology q, ton Eth/per
EPC_{k}^{K} = existing production capacity of distribution center k, ton blend/per
FCN_{dg} = fixed capital investment for new type g gas stations within retail center d, \$/GS
FCR_{dv} = fixed capital investment for type v retrofits within retail center d, \$/GS
FIC_{ks}^{DC} = fixed investment cost on distribution center k of size s, \$
FIC_{jqs}^{EP} = fixed investment cost on ethanol plant j with production technology q of size s, \$
FIC_{i}^{HS} = fixed investment cost on harvesting site i, \$
FTC_{bmt}^{B} = fixed transportation cost of biomass b by transportation mode m in time period t, \$/ton B
FTC_{pmt}^{P} = fixed transportation cost of product p by transportation mode m in time period t, \$/ton P
$LBPC_{jq}^{EP}$ = lower bound on production capacity of ethanol plant j with production technology q, ton Eth/per
$LBPC_{k}^{DC}$ = lower bound on production capacity of distribution center k, ton blend/repl
$NINIT_{dga}$ = amount of type g existing gas stations with age a within retail center d No GS
NJ_{qst} = max number of ethanol plants per production technology q, size s and year t, no Eth plants
$NJ_{j\ t}^{TOT}$ = max number of ethanol plants per year t and per potential location j, no Eth plants
NK_{st} = max number of distribution centers per size s and year t, no DC
$NK_{k\ t}^{TOT}$ = max number of distribution centers per year t and per potential location k, no DC
PB_p = percentage of fuel demand corresponding to product p, %
PC_{ks}^{DC} = production capacity of distribution center k and size s, ton blend/repl
PC_{jqs}^{EP} = production capacity of ethanol plant j with production technology q and size s, ton Eth/per
PC_{dg}^{D} = production capacity of type g gas stations within retail center d, ton blend/GS
PTO_{dgt}^{G} = proportional time of construction of type g new gas stations within retail center d in time period t, Idle h/h
PTO_{dvt}^{V} = proportional time of construction of type v retrofitted gas stations within retail center d in time period t, Idle h/h
SC_{bjt}^{BJ} = storage capacity of biomass b in ethanol plant j in time period t, ton B/per
SC_{dgp}^{MAX} = maximal capacity of the underground tanks that stored product p in type g gas stations within retail center d, ton P/per
SC_{dgp}^{MIN} = minimal capacity of the underground tanks that stored product p in type g gas stations within retail center d, ton P/per
SC_{dpt}^{PD} = storage capacity of product p in retail center d in time period t, ton P/per
SC_{jpt}^{PJ} = storage capacity of product p in ethanol plant j in time period t, ton P/per
SC_{kpt}^{PK} = storage capacity of product p in distribution center k in time period t, ton P/per
TOR_{dt}^{D} = turnover ratio of retail center d within time period t, days/repl
TOR_{jt}^{J} = turnover ratio of ethanol plant j within time period t, repl/per
TOR_{kt}^{K} = turnover ratio of distribution center k within time period t, repl/per
VIC_{i}^{HS} = variable investment cost on harvesting site I, \$/ton B
VPC_{dpt}^{D} = variable production cost of product p in retail center d in time period t, \$/ton P
VPC_{bit}^{I} = variable production cost of biomass b in harvesting site i in time period t, \$/ton B
VPC_{jqt}^{J} = variable production cost in ethanol plant j with production technology q in Time period t, \$/ton E85
VPC_{kt}^{K} = variable production cost in distribution center k in time period t, \$/ton blend
VTC_{bmt}^{B} = variable transportation cost of biomass b by mode of transportation m in time period t, \$/ton B.km
VTC_{pmt}^{P} = variable transportation cost of product p by mode of transportation m in time period t, \$/ton P.km
WC_{imt} = weight capacity of transportation mode m from harvesting site i in time period t, ton B/per

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