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Modeling the Distribution and Transshipment of Refined Oil Products

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About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

This publication is also available in Arabic.

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Key Points

KAPSARC has developed an optimization model to characterize the distribution of oil products after the refining stage. The model ensures that the demand for any group of refined oil products is simultaneously met while minimizing the social costs associated with the distribution system. The distribution system moves products from oil refineries or import terminals to petroleum bulk plants using multiple modes of transport. Then, the products are moved from bulk plants to customers via trucking or pipeline transport. In this setting, the customers are potential fuel wholesalers or retailers, such as gasoline stations and liquefied petroleum gas packaging facilities. The model's attributes are as follows:

- It determines whether to transport fuel by pipeline, truck or ship by minimizing costs.

- It considers capacity constraints for storage and loading and unloading trucks at bulk plants and pipelines across the network.

- It allows for investments in storage capacity at bulk plants and pipelines.

- It considers the geographical coordinates of the locations of all the elements within the distribution system. This feature primarily allows users to automate distance computations as locations change or new locations are built.

- It enables users to run future scenarios by considering different fuel demand and refining supply projections.

Introduction

KAPSARC has developed an optimization model to characterize the distribution system for some or all refined oil products. In the distribution system, oil products are first transported from refineries' gates to bulk plants. Products can then be stored at the bulk plants if needed and are ultimately transported to distributors and wholesalers. Figure 1 provides a stylized schematic of the supply chain used for the model.

The model can be run over multiple years with a particular time horizon, or over a single time period with or without investment. Although it can be applied to any region worldwide, we have specified for a case study of Saudi Arabia. That specification incorporates the transport of several fuels from the individual oil refineries to existing and prospective bulk plants via three possible modes of transport: pipelines, trucking and marine travel around the Arabian Peninsula. It may also choose to transport fuel from one bulk plant to another. The specification for Saudi Arabia also includes 486 demand centers that can interact with the bulk plants. The locations of these elements are defined by their latitudinal and longitudinal coordinates. The model considers fuel-specific pipeline and trucking capacity constraints and costs throughout this network.

Some components of the model may be supported by Geographical Information System (GIS) software. GIS software can provide visualization tools for the model results and improve distance parameterization when the trucking mode of transport is used. It can also validate the locations of any proposed bulk plants.

This study describes the model's formulation and presents the results of an illustrative scenario run. Some of the key outputs are shown to demonstrate the model's potential uses. Analysts can use the model to explore many issues, including:

> The marginal costs at each bulk plant or demand center analyzed.

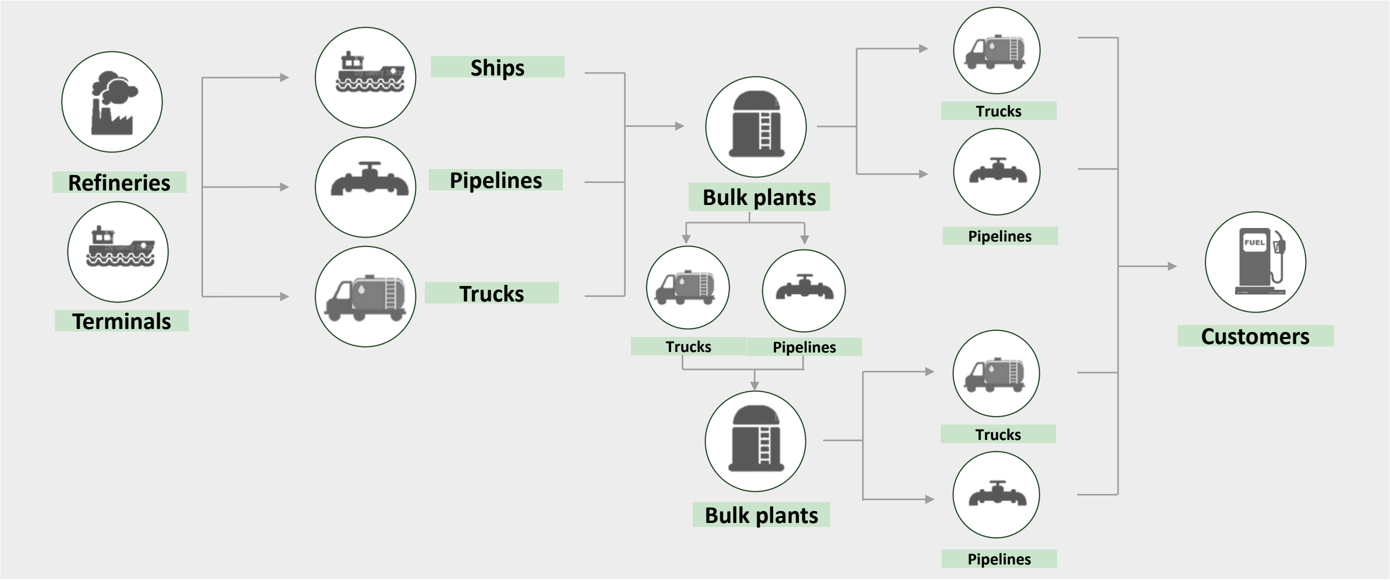
> The most susceptible areas in the event of an outage and the best policy measures to remedy any vulnerabilities.

> The effects of changes in the regional demand for fuels in the near future on the spatial distribution of bulk plants.

> New bulk plant storage capacities or the expansion of the pipeline network.

> The shares of each mode of transport from each refinery to each bulk plant and from each bulk plant to the demand centers.

Figure 1. Simplified fuel distribution network.



Source: KAPSARC.

Related work

This type of bottom-up approach is common for analyses like ours. For instance, Herran, De La Cruz and de Andres (2010) use a similar optimization method. They assess intraday (i.e., short-term without investment) transport planning for several oil products through a pipeline system. Our study differs from theirs in a few ways. First, our goal is to assess long-term planning. Second, their method assigns integer values to some variables. Third, we include multiple modes of transport. ICF, an advisory group, uses the same optimization approach to analyze the crude oil network in the U.S. and Canada (API 2017).

More recently, Wang et al. (2019, 2021) assess the distribution of refined oil products using an optimization model with similar constraints to those applied in this study. They focus on the reliability of the distribution system. We are going to consider the material balance constraints they included in their work. However, their models restrict some variables to integer values, whereas our model is purely continuous. We used a conventional linear programming method because we aim to produce a planning tool that could be run in real-life over many time periods. Moreover, real-life distribution systems may contain dozens of oil refineries and/or petroleum bulk plants (PBPs), several fuel products, and hundreds of demand centers. An integer program would require more time to find a solution than the tried simplex algorithm. Our model also includes additional constraints related to trucking and pipeline transport and a different objective function. We consider constraints that allow for various fuel groups to share an existing loading bay or inter-PBP pipeline. For instance, a single PBP may have several loading bays for trucks, and each of those bays could have different fuels sharing its working capacity. The subsequent section explains the formulation mathematically.

Approach

The transshipment network model reflects the entire fuel distribution system, from the outputs of oil refineries and import terminals to distribution plants and fuel wholesalers. A user may incorporate as many fuels in the model depending on the goal of the analysis. If more than one fuel is incorporated, all the fuels are considered simultaneously to account for any transport capacity that is shared between them.

The model may be run over time to analyze the long-term characteristics of the distribution system. Monthly or annual time steps may be assigned to any year or years in the time horizon. The model uses an optimization approach to make operational and investment decisions to meet customer demand while minimizing the network's social costs. Here, the social costs include capital costs and fixed and variable operations and maintenance costs. They also include the values assigned to the fuels, and the externalities attributed to the carbon dioxide emissions and road accidents stemming from trucking.

The formulation takes the geographical coordinates of existing infrastructure as inputs. If applicable, it then identifies the optimal geographical coordinates for new petroleum bulk plant (PBP) locations. It estimates the investment costs to construct the corresponding pipeline capacities. The model can compute the distances between oil refineries, PBPs and demand centers in kilometers. This capability simplifies the spatial representation of the network and enables a fine spatial resolution.

Another useful capability of the model is that it allows for certain investments. The storage capacities of existing or new PBPs can be expanded with investments. Additionally, the capacities of pipelines from refineries to PBPs or from PBPs to customers may be increased. The model currently assumes that the design and construction of a PBP takes two years and that of a pipeline takes three years. However, model users can change those parameters if needed. The costs of these investments per unit distance and volume are taken from Verma et al. (2017) and a study performed for the American Petroleum Institute (API 2017). The Appendix provides additional information on these assumptions.

Another key feature of the model version is the ability to make investments just in trucking loading bays. The model is able to determine whether investment in expanding loading bay capacity or in pipeline capacity between bulk plants or bulk plants-to-demand centers is more cost effective at existing or new BPs. Of course, this assumes there is enough land area available for expansion of the trucking bays. The true feasibility of these bays will be contingent on the availability of space and road access. This evaluation must be conducted at the individual bulk plants. ICF (2018) uses an investment cost of 2 dollars per gallon per day for a bulk plant's loading bays, which comes out to 84 dollars per barrel per day. This cost encompasses extending the rack, canopy, piping, pumps, vapor control units, loading control, valves, and loading arms. We estimate the bays' annual fixed operational costs to be 2% of the investment cost. A 10% discount rate is the default for valuing costs in future years, but model users can change this parameter.

In addition to storage at bulk plants, the model incorporates flows of refined oil products via multiple modes of transport: pipelines, trucking and maritime shipping. Transport from refineries or terminals to bulk plants can be in the form of any of the three options. Transport between bulk plants and from bulk plants to demand centers is restricted to pipeline and trucking. Existing pipeline capacities may be input as initial conditions. Also, the available modes of transportation may depend on the locations of refineries, bulk plants or demand centers. For example, if a refinery and a bulk station are landlocked, then the model can enforce no maritime shipping between them.

An important constraint on trucking is the loading and unloading capacities associated with each PBP. Those capacities are generally set based on groups of fuels in addition to individual fuels. For instance, diesel and motor gasoline usually share the same unloading bay. Thus, in this example, the shares of diesel and motor gasoline transported by truck are endogenous to the model. The initial pipeline infrastructure is taken as an input to the model.

Decision makers may build out additional pipelines to minimize carbon dioxide emissions, which are generated only by trucking. The assumptions underpinning the valuation of carbon dioxide are detailed in the Appendix. Another externality cost taken into consideration deals with the increased prevalence or risk of road accidents when using trucks. The cost associated with road accidents[2] was taken from a study performed by Delft (2011) for the European Union. In that study, the costs of climate change impact and road accidents comprised nearly 60% of the total externality cost borne by heavy duty vehicles.

KAPSARC provides typical capital and operational cost metrics to use as inputs to the model. These metrics include the costs of pipeline, ship and truck transport from refineries to PBPs, between PBPs, and from PBPs to customers by unit distance and volume. These costs depend on the performance characteristics of the transport modes and the distances from origins to destinations. The costs of fuel for trucks and electricity for pipelines are incorporated as variables through time to account for changing energy prices. Model users can input their own independent metrics if desired. The associated inputs are tabulated in the Appendix.

The values of the refined oil products are also included in the overall social costs. These values are assigned by the model user or policymakers and may differ depending on the supply source. The prices of any imported fuels are their projected international market prices. The production costs in some geographical areas may be below international prices. In such cases, the prices of domestically produced fuels may be specified as lower than the prices of imported fuels. The upper bound of the domestic fuel supply can be defined as the production of each fuel considered in the model by each domestic refinery in the system. The model considers the distribution system after the fuels leave the refineries. The actual refineries may optimize their production for the slate of crude oil grades processed, domestic demand and prices, and international demand and prices.

To summarize, some of the data inputs and model outputs are as follows.

Data inputs required for the base year

- Geographical coordinates of existing oil refineries, import terminals, PBPs and demand centers
- Domestic supply of refined oil products
- Existing storage capacity of each PBP by fuel
- Capacities of the pipelines between each oil refinery and PBP
- Pipeline capacities between any two PBPs
- Loading and unloading capacities of each PBP by fuel
- Capital and operational costs
- Customer demand by fuel

Model outputs

- Investments in new PBPs and pipelines (including their locations and capacities)
- Flow of each fuel through the network by transport mode
- Total, investment and operational transportation costs of the network
- Marginal costs of each fuel type at the point of sale

Figure 1 shows the general structure of the model. However, an actual fuel distribution system and model consists of many oil refineries, PBPs and fuel retailers. The equations and inequalities that comprise the linear program are further described as follows. The model files , which are written in the General Algebraic Modeling System (GAMS n.d.), may be found at https://github.com/womatar3/FuelDistribution [4].

Model formulation

Sets

r = {oil refineries or import terminals}

l and l2 = {PBPs}

d = {demand centers}

m = {transportation modes}

f = {fuels}

$fgroup$ = {fuel groups} (to map fuels into groups)

t = {time in years}

Parameters (inputs)

$\boldsymbol{a_{f,l,t}}$ = fixed operational cost for petroleum bulk plant (*$/barrel*)

$\boldsymbol{b_{f,l,t}}$ = capital cost for bulk plant (*$/barrel*)

$\boldsymbol{c_{f,m,r,l,t}}$ = variable transport operational cost from r to l by m over time (*$/bpd*)

$\boldsymbol{c'_{f,m,l,d,t}}$ = variable transport operational cost from l to d by m over time (*$/bpd*)

$\boldsymbol{c''_{f,m,l,l2,t}}$ = variable transport operational cost from l to l_2 by m over time (*$/bpd*)

$\boldsymbol{d_{r,l,t}}$ = fixed operations cost of pipeline from r to l (*$/bpd*)

$\boldsymbol{d'_{l,d,t}}$ = fixed operations cost of pipeline from l to d (*$/bpd*)

$\boldsymbol{d''_{l,l2,t}}$ = fixed operations cost of pipeline from l to l2 (*$/bpd*)

$\boldsymbol{e_{r,l,t}}$ = capital cost for pipeline from r to l (*$/bpd*)

$\boldsymbol{e'_{l,d,t}}$ = capital cost for pipeline from l to d (*$/bpd*)

$\boldsymbol{e''_{l,l2,t}}$ = capital cost for pipeline from l to l_2 (*$/bpd*)

$\boldsymbol{v_{f,t}}$ = fuel value or price of oil products (*$/barrel*)

$\boldsymbol{g_{f,l,d}}$ = road accident costs from l to d ($/(*bpd·km*))

$\boldsymbol{g'_{f,r,l}}$ = road accident costs from r to l ($/(*bpd·km*))

$\boldsymbol{\varphi_t}$ = discount factors over time

$\boldsymbol{tc_{1_{f,l}}}$ = trucking capacity from l to d (in thousand bpd)

$\boldsymbol{tc_{2_{f,l}}}$ = trucking capacity from r to l (in thousand bpd)

$\boldsymbol{rc_{r,f,t}}$ = domestic fuel f availability at r throughout time (in thousand bpd)

ur = utilization rate (dimensionless)

$\boldsymbol{CO2cst_t}$ = social cost of carbon dioxide emissions per ton through time (in $/tonne)

$CO2emdiesel$ = tonnes of carbon dioxide emitted per L of diesel burned in a mobile engine (tonnes/L)

$\boldsymbol{tsdrl_{r,l}}$ = liters of diesel used per bpd transported from r to l (L)

$\boldsymbol{tsdld_{l,d}}$ = liters of diesel used per bpd transported from l to d (L)

$\boldsymbol{y_{f,d,t}}$ = amount of fuel demanded at d (thousand bpd)

Variables (outputs; all the variables listed also have a constraint to be greater than or equal to 0)

$(\boldsymbol{qld}_{f,m,l,d,mo,t}, \boldsymbol{qld2}_{f,m,l,d,mo,t}, \boldsymbol{qld3}_{f,m,l,d,mo,t})$ = amount of f transported from l to d (thousand bpd)

$\boldsymbol{qrl}_{f,m,r,l,mo,t}$ = amount of f transported from r to l by m (thousand bpd)

$(\boldsymbol{qll}_{f,m,l,l2,mo,t}, \boldsymbol{qll2}_{f,m,l2,l3,mo,t})$ = amount of f transported from l to $l2$ by pipeline only (thousand bpd)

$\boldsymbol{qstin}_{f,l,mo,t}$ = amount of f taken into storage at l (thousand bpd)

$\boldsymbol{qstout}_{f,l,mo,t}$ = amount of f taken out of storage at l (thousand barrels) *

$\boldsymbol{qst}_{f,l,mo,t}$ = amount of f stored at l (thousand bpd) *

$\boldsymbol{ex}_{f,l,t}$ = existing storage capacity at petroleum bulk plant (thousand barrels) *

$\boldsymbol{LBex}_{fgroup,l,t}$ = existing trucking loading bay capacity at petroleum bulk plant (thousand barrels) *

$\boldsymbol{pexrl}_{fgroup,f,r,l,t}$ = existing pipeline capacity from r to l for f (thousand bpd) *

$\boldsymbol{pexld}_{f,l,d,t}$ = existing pipeline capacity from l to d for f (thousand bpd) *

$\boldsymbol{bl}_{f,l,t}$ = built storage capacity at petroleum bulk station (thousand barrels)

$\boldsymbol{LBbl}_{fgroup,l,t}$ = built trucking loading bay capacity at petroleum bulk plant (thousand barrels) *

$\boldsymbol{pblrl}_{fgroup,f,r,l,t}$ = built pipeline capacity from r to l for f (thousand bpd)

$\boldsymbol{pblld}_{f,l,d,t}$ = built pipeline capacity from l to d for f (thousand bpd)

$\boldsymbol{pexll}_{fgroup,l,l2,t}$ = existing pipeline capacity from l to $l2$ for f (thousand bpd) *

$\boldsymbol{pblll}_{fgroup,l,l2,t}$ = built pipeline capacity from l to l2 for f (thousand bpd)

$\boldsymbol{fc}_{f,l,t}$ = value attributed to fuel f over time (in thousand $)

$\boldsymbol{CO2soccst}_{t}$ = social cost of carbon dioxide emissions over time (in thousand $)

* Initial conditions are required.

Note: bpd = barrels per day; km = kilometers.

Approach

The following problem minimizes the total fuel distribution network costs in thousands of U.S. dollars.:

- The part highlighted in green represents private costs to the operating company or companies.
- The part highlighted in orange is the value attributed to the oil products considered.
- The part highlighted in blue shows the externality costs associated with the road accidents.
- The part highlighted in gray represents the social cost of carbon dioxide.

The sum of these costs makes up the social costs in this model. There are conditions to restrict some variables, like those for construction lead time or shipping modes, which appear in the model code but are not shown in the formulation below. For instance, there are restrictions on which variables are included in the program based on the combination of the monthly and annual time steps considered. The quantity variables are defined in barrels per day, which means that the values are either multiplied by the share of each month in the year or by 1 if it is an annual value. Also, the quantities transported by trucking only operate if there are unloading and loading bay capacities at the bulk plants.

$$
\begin{aligned}
minimize \sum_{l,t} \Bigg[\sum_{f} \Bigg(& fc_{f,l,t} + a_{f,l,t}(ex_{f,l,t} + bl_{f,l,t}) + b_{f,l,t} bl_{f,l,t} \\
& + \sum_{m,mo,d} \left(c_{f,m,l,d,t}\left[qld_{f,m,l,d,mo,t} + qld2_{f,m,l,d,mo,t} + qld3_{f,m,l,d,mo,t}\right]\right) \\
& + \sum_{m,mo,r} \left(c'_{f,m,r,l,t} qrl_{f,m,r,l,mo,t}\right) + \sum_{m,mo,r} \left(c''_{f,m,l,l2,t}\left[qll_{f,m,l,l2,mo,t} + qll2_{f,m,l,l2,mo,t}\right]\right) \Bigg) \\
& + \sum_{fgroup} a'_t(LBex_t + LBbl_t) + b'_t LBbl_t \\
& + \sum_{r,fgroup} \left(d_{r,l,t}\left(pexrl_{fgroup,r,l,t} + pblrl_{fgroup,r,l,t}\right) + e_{r,l,t} pblrl_{fgroup,r,l,t}\right) \\
& + \sum_{d} \left(d'_{l,d,t}\left(pexld_{l,d,t} + pblld_{l,d,t}\right) + e'_{l,d,t} pblld_{l,d,t}\right) \\
& + \sum_{d,fgroup} \left(d''_{l,l2,t}\left(pexll_{fgroup,l,l2,t} + pblll_{fgroup,l,l2,t}\right) + e''_{l,l2,t} pblll_{fgroup,l,l2,t}\right) \\
& + \sum_{mo,d} \left(g_{f,l,d}\left[qld_{f,truck,l,d,mo,t} + qld2_{f,truck,l,d,mo,t} + qld3_{f,truck,l,d,mo,t}\right]\right) \\
& + \sum_{mo,r} \left(g'_{f,r,l} qrl_{f,truck,r,l,mo,t}\right) \\
& + \sum_{mo,l2} \left(g''_{f,l,l2}\left[qll_{f,truck,l,l2,mo,t} + qll2_{f,truck,l,l2,mo,t}\right]\right) \Bigg] \varphi_t + \sum_{t} CO2soccst_t \varphi_t
\end{aligned}
$$

Subject to

Constraint to balance the storage capacity of l over time (except when t is the last year in the horizon)

$$ex_{f,l,t} + bl_{f,l,t} = ex_{f,l,t+1}$$

Three constraints to balance the pipeline capacity from r to l, between bulk plants, and l to d over time (except when t is the last year in the horizon; modeling fuel-specific pipeline capacities may be specified in the transport activity variables).

$$pexrl_{fgroup,r,l,t} + pblrl_{fgroup,r,l,t} = pexrl_{fgroup,r,l,t+1}$$

$$pexld_{l,d,t} + pblld_{l,d,t} = pexld_{l,d,t+1}$$

$$pexll_{fgroup,l,l2,t} + pblll_{fgroup,l,l2,t} = pexll_{fgroup,l,l2,t+1}$$

Constraint to balance trucking loading bay capacity at l (except when t is the last year in the horizon).

$$LBex_{fgroup,l,t} + LBbl_{fgroup,l,t} = LBex_{fgroup,l,t+1}$$

These five constraints ensure the fuel amounts transported from r to l, between bulk plants, and from l to d by pipeline, do not exceed the capacity. In addition, limits are imposed on the variables to ensure adherence to fuel-specific pipeline capacity constraints.

$$\sum_{f} qrl_{f,pipeline,r,l,mo,t} \leq \sum_{fgroup} \left(pexrl_{fgroup,r,l,t} + pblrl_{fgroup,r,l,t}\right)$$

$$qrl_{f,pipeline,r,l,mo,t} \leq \sum_{fgroup\ (if\ f\ \text{is in}\ fgroup)} \left(pexrl_{fgroup,r,l,t} + pblrl_{fgroup,r,l,t}\right)$$

$$\sum_{f} qld_{f,pipeline,l,d,mo,t} + \sum_{f} qld2_{f,pipeline,l,d,mo,t} + \sum_{f} qld3_{f,pipeline,l,d,mo,t} \leq pexld_{l,d,t} + pblld_{l,d,t}$$

$$\sum_{f} qll_{f,pipeline,l,l2,mo,t} + \sum_{f} qll2_{f,pipeline,l,l2,mo,t} \leq \sum_{fgroup} \left(pexll_{fgroup,l,l2,t} + pblll_{fgroup,l,2,t}\right)$$

$$\begin{aligned} & qll_{f,pipeline,l,l2,mo,t} + qll2_{f,pipeline,l,l2,mo,t} \\ & \quad \leq \sum_{fgroup\ (if\ f\ \text{is in}\ fgroup)} \left(pexll_{fgroup,l,l2,t} + pblll_{fgroup,l,2,t}\right) \end{aligned}$$

Approach

Constraints to cap the trucking of fuels from l to d or from r to l (if element(s) of f map into $f$group)

$$\sum_{f,d}\left(qld_{f,truck,l,d,mo,t} + qld2_{f,truck,l,d,mo,t} + qld3_{f,truck,l,d,mo,t}\right) + \sum_{f,l2}\left(qll_{f,truck,l,l2,mo,t} + qll2_{f,truck,l,l2,mo,t}\right) \le \sum_{fgroup}\left(LBex_{fgroup,l,t} + LBbl_{fgroup,l,t}\right)$$

$$\sum_{d}\left(qld_{f,truck,l,d,mo,t} + qld2_{f,truck,l,d,mo,t} + qld3_{f,truck,l,d,mo,t}\right) + \sum_{l2}\left(qll_{f,truck,l,l2,mo,t} + qll2_{f,truck,l,l2,mo,t}\right) \le \sum_{fgroup\ (if\ f\ is\ in\ fgroup)}\left(LBex_{fgroup,l,t} + LBbl_{fgroup,l,t}\right)$$

$$\sum_{f,r} qrl_{f,truck,r,l,mo,t} + \sum_{f,l2}\left(qll_{f,truck,l,l2,mo,t} + qll2_{f,truck,l,l2,mo,t}\right) \le \sum_{fgroup} tc_{2_{fgroup,l}}$$

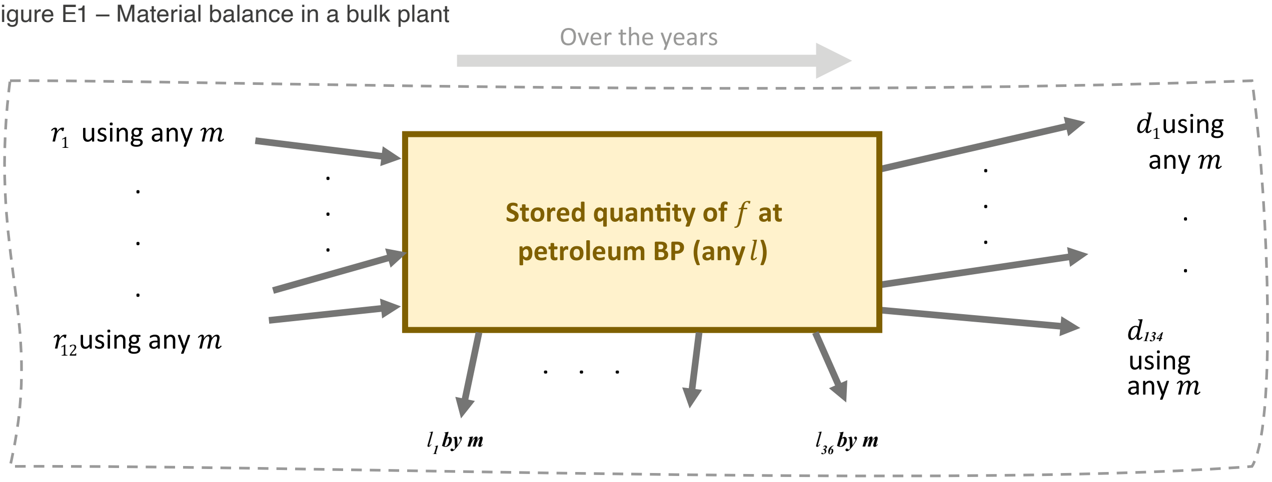
$$\sum_{r} qrl_{f,truck,r,l,mo,t} + \sum_{l2}\left(qll_{f,truck,l,l2,mo,t} + qll2_{f,truck,l,l2,mo,t}\right) \le \sum_{fgroup\ (if\ f\ is\ in\ fgroup)} tc_{2_{fgroup,l}}$$

At the interface between r, l, and d, this equation ensures continuity in the supply chain. This is the continuity equation with constant mass densities over time for each fuel (Figure E1). The model allows for the pipeline and trucking of fuels between BPs. The maritime shipping mode is restricted to between BPs.

$$\textstyle\sum_{m,r} qrl_{f,m,r,l,mo,t} - \sum_{m,d} qld_{f,m,l,d,mo,t} - \sum_{m,l2} qll_{f,m,l,l2,mo,t} = qstin_{f,l,mo,t} - qstout_{f,l,mo,t}$$

$$\sum_{m,r} qrl_{f,m,r,l,mo,t} - \sum_{m,d} qld_{f,m,l,d,mo,t} - \sum_{m,l2} qll_{f,m,l,l2,mo,t} = qstin_{f,l,mo,t} - qstout_{f,l,mo,t}$$

Figure E1 – Material balance in a bulk plant



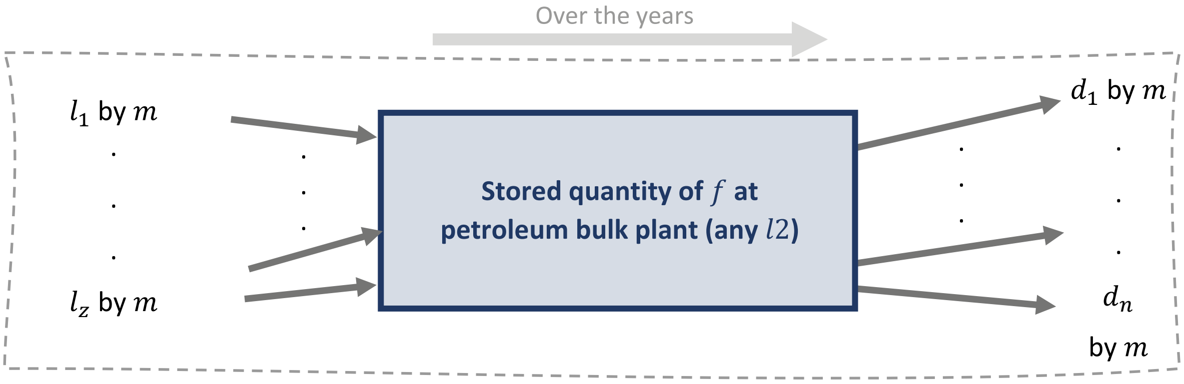
Source: KAPSARC.

Restricted to transport by pipeline or trucks, the following two equations represent BPs that are connected to other BPs. These are the continuity equations with constant mass densities over time for each fuel.

Figures E2 and E3 allow for a BP connected to another BP that can transfer to another BP. Figure E3 shows the final destination of a transport fuel by showing one BP attached to other BPs. We did it this way to untangle the quantity delivered by a tertiary BP. l_1 to l_36 are the same in figures E1 to E3.

$$\sum_{m,l} qll_{f,m,l,l2,mo,t} - \sum_{m,l3} qll_{f,m,l2,l3,mo,t} - \sum_{m,d} qld2_{f,m,l2,d,mo,t} = qstin_{f,l2,mo,t} - qstout_{f,l2,mo,t}$$

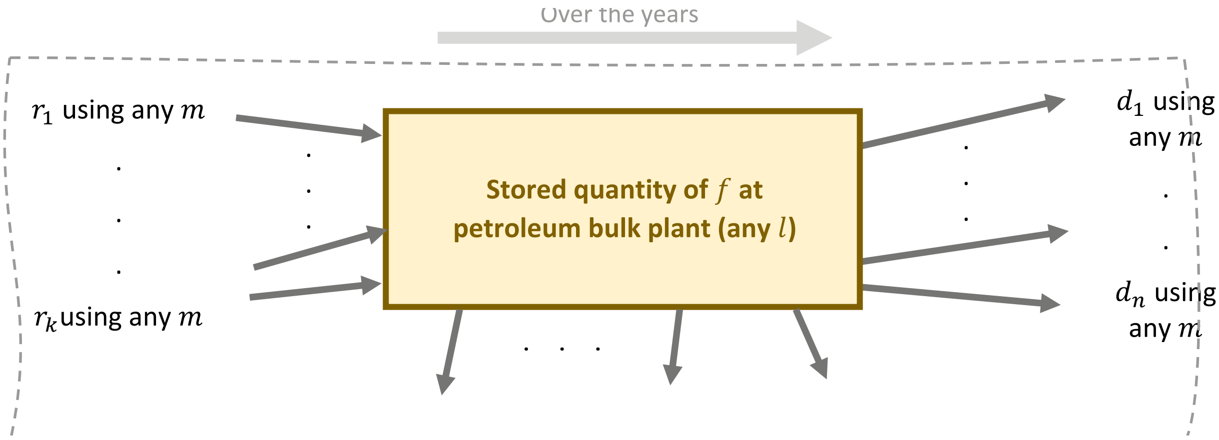
Figure E2 – Material balance in an intermediate BP connected to another BP



Source: KAPSARC.

$$\sum_{m,l2} qll_{f,m,l2,l3,mo,t} - \sum_{m,d} qld3_{f,m,l3,d,mo,t} = qstin_{f,l3,mo,t} - qstout_{f,l3,mo,t}$$

Figure E3 – Material balance in a final BP connected to another BP



Source: KAPSARC.

Equation to balance storage at l over time (this equation is highly conditioned to only include certain variables at each monthly time step. It is only shown below for annual time steps)

$$qstin_{f,l,mo,t} - qstout_{f,l,mo,t} + qst_{f,l,mo,t-1} = qst_{f,l,mo,t}$$

Constraint to ensure supply of f from r does not exceed the availability from r (maritime shipments only from the east coast to the west coast or from Yanbu terminal to the Duba, Jeddah, and Jizan terminals)

$$\sum_{m,l} qrl_{f,m,r,l,mo,t} \leq rc_{r,f,mo,t}$$

Constraint to ensure amount of each fuel stored by l does not exceed storage capacity at l ($\sigma_{mo,t}$ is a factor that scales to monthly or yearly number of days)

$$qst_{f,l,mo,t} \leq \frac{ur \cdot \left(ex_{f,l,t} + bl_{f,l,t}\right)}{\sigma_{mo,t}}$$

Constraint to impose a minimum storage level if the Ministry of Energy wanted to regulate how much is stored to ensure supply (could be applied to certain BPs)

$$qst_{f,l,mo,t} \geq \mu \sum_{d,m} \left(qld_{f,m,l,d,mo,t} + qld2_{f,m,l,d,mo,t} + qld3_{f,m,l,d,mo,t}\right)$$

Constraint to ensure demand is met at d for each f (no maritime shipments)

$$\sum_{m,l}\left(qld_{f,m,l,d,mo,t} + qld2_{f,m,l,d,mo,t} + qld3_{f,m,l,d,mo,t}\right) \geq y_{f,d,mo,t}$$

Equation to sum the value of fuels ($\sigma_{mo,t}$ is a factor that scales to monthly or yearly number of days)

$$v_{f,t} \sum_{m,,mo,r} qrl_{f,m,r,l,mo,t} \cdot \sigma_{mo,t} = fc_{f,l,t}$$

Equation to sum the social cost of CO2 emitted by trucking fuel from a refinery to a BP, between BPs, and from a BP to a demand center

$$\begin{aligned} CO2cst_t CO2emdiesel \Bigg(& \sum_{f,r,mo,l} tsdrl_{r,l} qrl_{f,truck,r,l,mo,t} \sigma_{mo,t} + \sum_{f,l,mo,d} tsdld_{l,d} qld_{f,truck,l,d,mo,t} \sigma_{mo,t} \\ & + \sum_{f,l,mo,d} tsdld_{l,d} qld2_{f,truck,l,d,mo,t} \sigma_{mo,t} + \sum_{f,l,mo,d} tsdld_{l,d} qld3_{f,truck,l,d,mo,t} \sigma_{mo,t} \\ & + \sum_{f,mo,l,l2} tsdll_{r,l} qll_{f,truck,l,l2,mo,t} \sigma_{mo,t} + \sum_{f,mo,l,l2} tsdll_{r,l} qll2_{f,truck,l,l2,mo,t} \sigma_{mo,t} \Bigg) \\ & = co2soccst_t CO2cst_t C \end{aligned}$$

Potential Ways to Use the Transshipment Model

The model can be used in several ways. First, it may be run to assess the status quo. It may also be run over time to gauge the effects of the evolution of demand or supply from refineries on operating decisions. It may also be used to examine the effects of one or more elements in the supply chain going out of service. We elaborate on these cases below.

1. Once calibrated to a base year, the model can be run in the short term to assess the current oil distribution landscape. In this case, no investments are allowed, and only existing pipeline and storage capacities are considered. This analysis allows the user to identify vulnerable demand centers. In this case, the model chooses between the transport options to minimize system costs and determines the marginal cost of demand at each demand center. Centers with the highest marginal costs are potentially susceptible.

2. The model can be run annually from the base year until some future year. In this case, the user can observe the effects of the evolution of fuel demand on investment and operational decisions in the distribution network. This analysis can help to determine new PBP locations. In this case, several possibilities for new PBP locations should be identified using GIS before the model is run because the Earth's curvature is non-linear. These options are inputted as additional PBP locations when running the optimization.

3. Finally, the model can highlight the impacts of outages. After running case 2 as a reference, a user can identify potential contingencies if a pipeline or PBP goes out of service. The model also indicates changes in the costs throughout the network as a result of an outage. The model shows the next least-cost operational decisions under an outage, and the outcomes can be compared to those in the base case.

In any of these cases, the model is free to decide to invest in PBPs or pipeline capacity. It chooses the modes of transport for refined fuels by minimizing social costs given the constraints. The option that minimizes social costs is selected as the ideal investment scenario.

Using the Model: An Illustration

We illustrate a brief scenario from 2021 to 2040, although model users may prefer to consider different time horizons. For model tractability, we restrict the illustration to a case were a PBP cannot transfer fuel to other PBPs. In this scenario, investments in bulk plant storage and in pipelines from refineries to bulk plants or bulk plants to customers are allowed. This scenario incorporates motor gasoline, diesel and kerosene.

All the data points described in this section are intended to illustrate the model. The analyzed system has two oil refineries, two bulk plants and no existing pipeline, as Table 1 shows. The model may choose to expand the pipeline infrastructure or maintain the current use of tanker trucks. The loading capacity for each bulk plant is 60,000 barrels a day. The unloading capacity is 59,000 barrels a day for gasoline and diesel as a group, and 59,000 barrels a day for kerosene alone. The refinery output levels increase at 2% per year. The values attributed to the oil products are listed in the Appendix. Model users have the flexibility to set the numbers of refineries, bulk plants, refined fuels and demand centers.

Table 1. Capacities and locations of oil refineries, bulk plants and pipelines.

Name and location	Output in the base year (thousand barrels a day)	
Refinery 1 (28.5N, 39E)	Motor gasoline	27.2
	Diesel	43.2
	Kerosene	12.0
Refinery 2 (22.5N, 35.5E)	Motor gasoline	20.8
	Diesel	32.0
	Kerosene	6.4
	Existing storage capacity (thousand barrels)	
Bulk Plant 1 (28N, 42E)	Motor gasoline	25
	Diesel	10
	Kerosene	0
Bulk Plant 2 (23N, 35E)	Motor gasoline	0
	Diesel	5
	Kerosene	15
	Existing pipeline capacity	
Refineries to bulk plants or bulk plants to customers	Zero initial capacity	

Source: KAPSARC inputs.

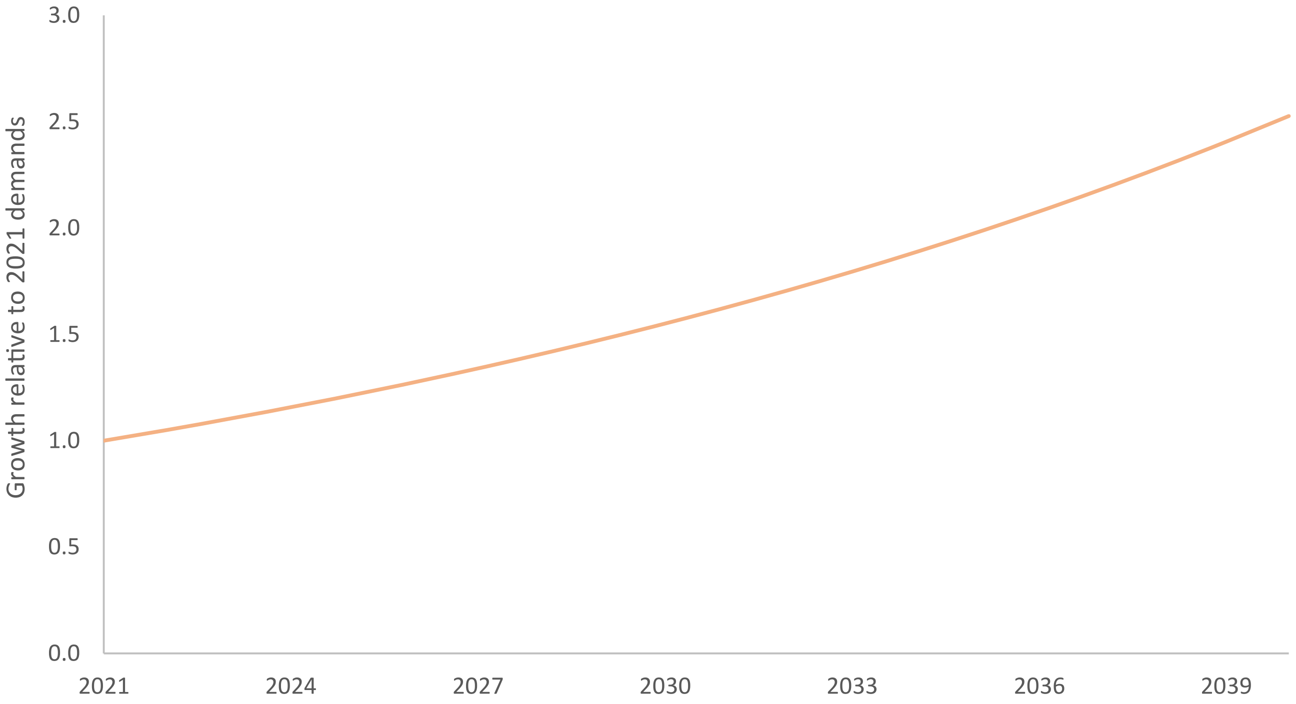
The demands at two locations for the three refined products considered are shown in Table 2. These values amount to a combined 32.4 million barrels in 2021. Figure 2 shows the assumptions regarding demand growth relative to the initial conditions.

Table 2. Demand for fuel at certain locations.

Name and location	Demand in 2021 (thousand barrels per day)	
Demand Center 1 (26N, 39E)	Motor gasoline	14
	Diesel	20
	Kerosene	10
Demand Center 2 (25N, 35E)	Motor gasoline	20
	Diesel	25
	Kerosene	0

Source: KAPSARC inputs.

Figure 2. Fuel demand growth scenario example used in the transshipment network model.

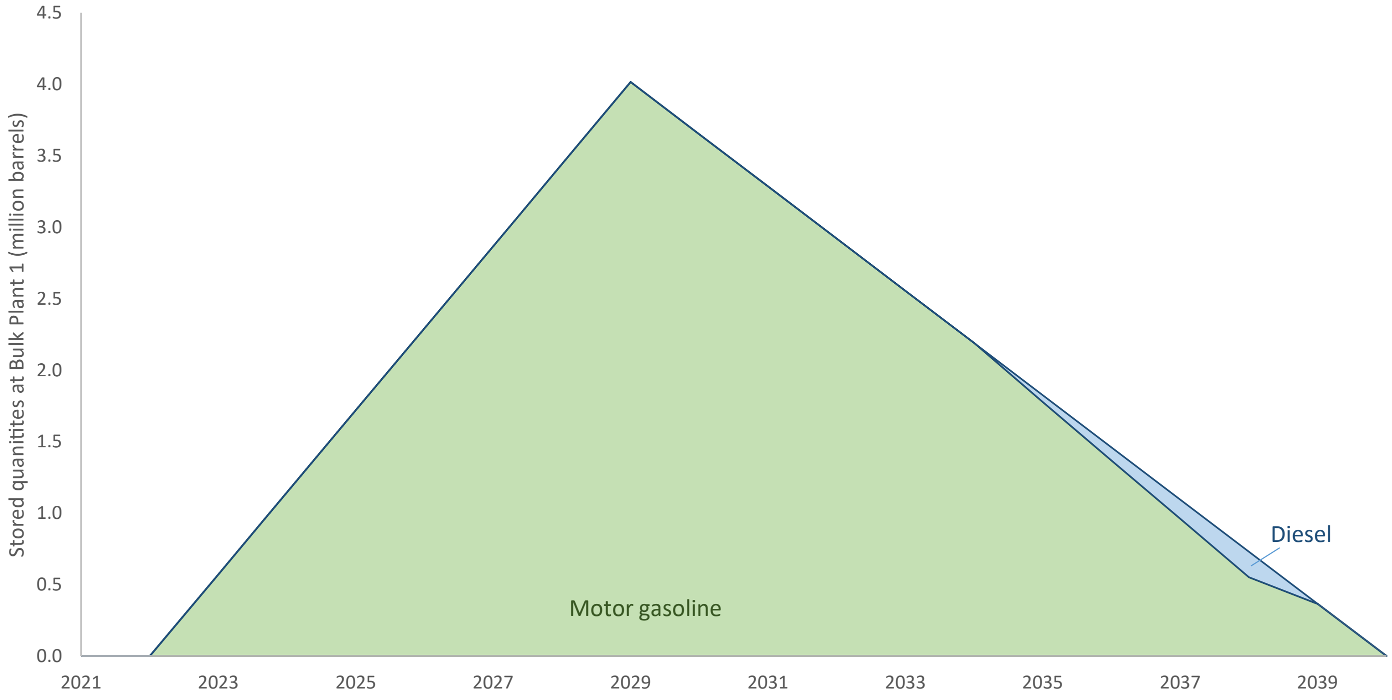


Source: KAPSARC input.

As explained previously, investments in storage capacity and pipelines are made to minimize total social costs. The first year that new storage capacity in bulk plants may be built is 2023. In this year, Bulk Plant 1 adds nearly 600,000 barrels of gasoline storage capacity, and Bulk Plant 2 adds 2.4 million barrels. Bulk Plant 2 builds a combined 755,000 barrels of additional storage capacity for diesel in 2036 and 2037. Because this scenario does not include imports, the storage capacity at bulk plants is related to oil refineries' production. If the refineries increased production, no additional storage would be needed.

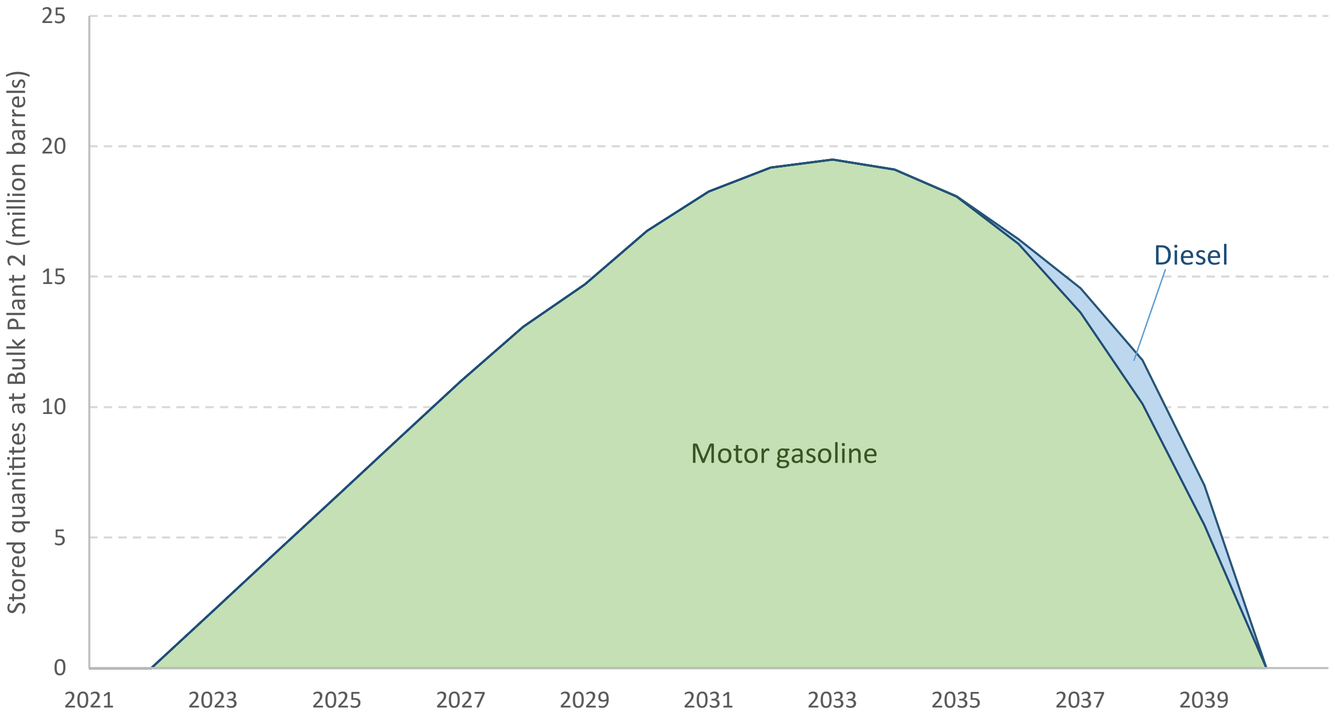
Figures 3a and 3b show the storage of gasoline and diesel at each bulk plant over the study period in millions of barrels. At its peak in 2029, the gasoline stored at Bulk Plant 1 can satisfy about half of daily demand at Demand Center 1. Alternatively, it can meet about 40% of daily demand at Demand Center 2. It can also provide gasoline to both demand centers in some combination. As another example, 4,600 barrels of diesel per day are stored at Bulk Plant 2 in 2037, equivalent to 8% of daily demand in that year. No kerosene is stored at either bulk plant.

Figure 3a. Storage at Bulk Plant 1 from 2021 to 2040.



Source: Model results.

Figure 3b. Storage at Bulk Plant 2 from 2021 to 2040.



Source: Model results.

Initially, no pipeline infrastructure exists. However, a pipeline between Refinery 2 and Bulk Plant 2 is developed in 2029. Two years later, a pipeline between Bulk Plant 2 and Demand Center 2 is created. The cumulative pipeline capacity between refineries and bulk plants built by 2040 is around 60,000 barrels per day. The capacity of pipelines between bulk plants and customers is nearly 80,000 barrels per day.

Moreover, information on the marginal costs of transporting each type of fuel to each demand center may be useful for identifying vulnerabilities. In this illustrative scenario, Table 3 shows marginal transport costs for each demand center in 2021, 2030 and 2040. Here, the marginal costs for motor gasoline and diesel are consistent at both demand centers, varying only at the thousandth decimal place. Demand Center 2 has no demand for kerosene, and, thus, no marginal cost is shown. Costs are generally lower in the future owing to discounting effects. However, the price of gasoline does not fall as drastically as the prices of other fuels. In fact, it is higher in 2040 than in 2030 because of storage costs at bulk plants.

Table 3. Marginal transport costs ($ per barrel) throughout the distribution system in 2021, 2030 and 2040.

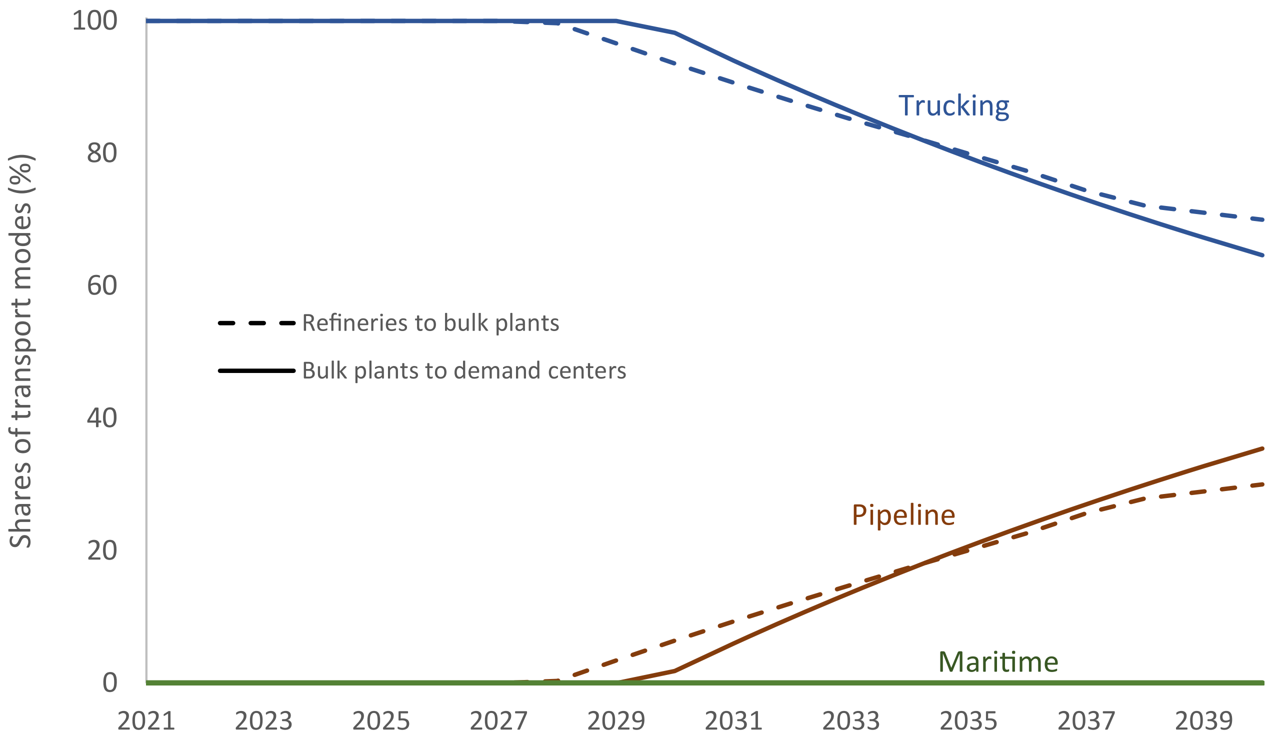
		2021	**2030**	**2040**
Demand Center 1	Motor gasoline	78.64	56.66	56.80
	Diesel	76.91	33.82	20.68
	Kerosene	70.82	31.02	13.57
Demand Center 2	Motor gasoline	78.64	56.66	56.80
	Diesel	76.91	33.82	20.68
	Kerosene	-	-	-

Source: Model results.

The overwhelming majority of the total social cost stems from the value placed on fuel transported from refineries. The next highest component of the total social cost is capital expenses, followed by associated fixed operations and maintenance costs. The variable cost of transportation comprises only slightly more than 1% of the social cost over the 20-year horizon. Trucking uses 39,000 liters of diesel in 2021, and consumption grows to about 100,000 liters by 2040. The carbon dioxide emitted by trucking is a miniscule portion of the present value of the total social cost over the study horizon.

Figure 4 illustrates the shares of fuel transported by truck, pipeline and ship between refineries and bulk plants and between bulk plants and demand centers. The first pipeline investment begins in 2028, resulting in a pipeline from Refinery 2 to Bulk Plant 2. The proportion of fuel transported by pipeline gradually rises to 30% by 2040. As the scenario incorporates two demand centers, transport to customers shifts to pipelines shortly thereafter. If fuel demand is dispersed across many demand points, investment in pipeline connections to customers may be less attractive. Pipelines are initially installed from Bulk Plant 2 to Demand Center 2 steadily but more quickly from 2031. However, no pipeline from Refinery 1 is built during the study period.

Figure 4. Shares of fuel by transport mode from 2021 to 2040.



Source: Model results.

Conclusion

This Methodology Paper presents a planning model that can analyze the distribution system of refined oil products. After leaving refineries, the fuels may be transported via multiple modes to bulk plants, where they can be stored. They can be transported between any two bulk plants by truck or pipeline as an intermediate step. They are then transported to wholesalers or distributors, usually by truck, although the model allows for investments in pipelines. This paper details the formulation and parameterization of the model and presents an illustrative case study. The model may be applied to any region worldwide.

The model is currently formulated in the GAMS environment as an optimization problem with perfect foresight. Future iterations may expand on the sector's ability to foresee information about the future. The model is designed to be run over one or multiple years. Any year in the time horizon may be specified to have monthly or annual time resolution. The formulation balances capacities over time given storage or transport constraints based on the relevant capacities. It also includes material balance equations that track the storage of each fuel at each bulk plant. The model takes the geographical coordinates of all elements in the distribution system as inputs. This feature not only provides the model user with fine spatial granularity but also eliminates the need to input potentially thousands of distances between elements. It also enables automatic updates of inter-element distances if elements are removed to reflect certain policy scenarios.

The formulation incorporates many nuances that characterize the distribution system. For instance, bulk plants have truck loading and unloading capacities for individual refined oil products. These loading and unloading capacities may also be shared by groups of several refined products. Furthermore, fuel demand may be satisfied by fuel imports and domestic production in the model. Future iterations of the model may incorporate monthly time steps within the annual time steps already considered.

This paper illustrates some of the models' key outputs. The scenario consists of two oil refineries, two bulk plants, two demand centers and three fuels. Storing more gasoline and diesel at Bulk Plant 2 than at Bulk Plant 1 minimizes social costs. The rationale for this decision is that the demand for fuel is greater at the demand center closest to Bulk Plant 2. Because this scenario does not include imports, the bulk plants' storage capacities are restricted to the oil refineries' production. If refineries produced more, no additional storage would be needed. The marginal costs of transporting fuels to customers are the same for both demand centers. In a more complex network, however, these costs may differ across demand centers. Additionally, the scenario has no initial pipeline capacity. However, transport from refineries to bulk plants starts gradually shifting to pipelines. Transport from bulk plants to customers shifts to pipelines shortly thereafter. If fuel demand is dispersed across many demand points, investment in pipeline connections to customers may be less attractive.

Appendix – Parameterization of the Model

The model user may set core inputs pertaining to storage capacity, pipeline capacity, the locations of all elements in the supply chain and the fuel quantities demanded. This section provides the basis for parameterizing the base assumptions and inputs aside from the core inputs. These inputs include the capital and operational costs associated with the various transport modes and bulk plants. Details on these inputs are shown in Table A1.

Table A1 shows the capital costs, fixed operations and maintenance costs, the inputs used to estimate variable operational costs and equipment designed lifetimes. For instance, the model calculates pipeline variable costs using engineering equations (e.g., the Reynolds number, friction coefficient equations and head loss in the pipe). Depending on the Reynolds number, the flow may be laminar, turbulent or in transition between the two. The model calculates the friction coefficient differently in each of those three cases. All the physical properties are taken from McQuiston, Parker and Spitler (2005).

International prices of refined oil products are used for import terminals or if local prices are the same as international prices. We take data on prices in the base year from the U.S. Energy Information Administration (EIA) and estimate their evolution over time. To parameterize the illustrative scenario, market prices for refined oil products in 2021 are taken from EIA (2022). After the base year, prices are determined using the projections of the Brent price in the Annual Energy Outlook 2021 (EIA 2021). The differences are assumed to remain the same over the entire study period.

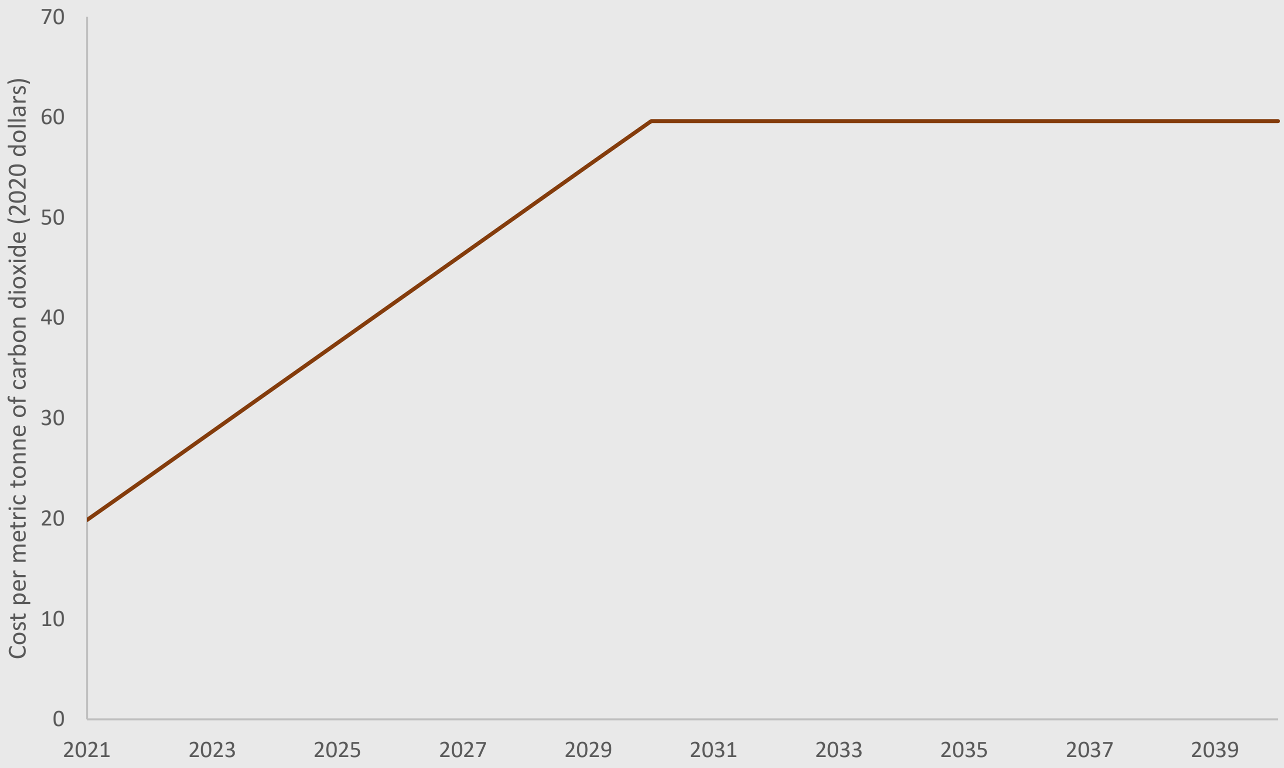
We calculate carbon dioxide's social cost by first estimating the amounts of diesel used to transport refined oil products via truck. Those estimates are then multiplied by the carbon dioxide content per unit of diesel provided by the U.S. Environmental Protection Agency (EPA) (EPA 2021). Carbon dioxide can be valued using the Intergovernmental Panel on Climate Change's estimates (IPCC 2018) for keeping the global mean temperature change to 1.5 degrees Celsius (°C) or 2°C above pre-industrial levels. Figure A1 shows these values from 2021 until 2040, which are inputs for the illustrative scenario.

Table A1. Inputs used to derive costs.

		Source of raw information
Storage capacity at distribution station performance and cost		
Capital cost ($ per barrel)*	15	API (2017)
Fixed operations and maintenance (O&M) costs	3% of capital costs	Author assumption
Designed lifetime (years)	30	KAPSARC assumption
Pipeline performance and cost		
Capital cost* ($ per km per bpd)	3.92	Calculated based on Verma et al. (2017)
*** Capital cost includes steel piping, inlet pump, booster pumps, road access and buildings along the line.**		
Pipeline and pump fixed O&M costs ($ per km per bpd)	0.022	Calculated based on Verma et al. (2017)
Diameter (inches)	33	Verma et al. (2017)
Flow rate (thousand bpd)	100	KAPSARC assumption
Pipe roughness (ft)	0.00015	McQuiston, Parker and Spitler (2005)
Pump efficiency (%)	80	KAPSARC assumption
Electricity price in 2021 ($ per MWh)	48	WERA (2022)
Designed lifetime (years)	30	IEA-ETSAP (2011)
Trucking performance and cost		
Price of diesel used for transport in 2021 (SAR per L)	0.63	Saudi Aramco (2022)
Truck fuel efficiency (km per L)	2.16	Marufuzzaman, Ekşioğlu and Hernandez (2015)
Fixed O&M costs ($ per km)	0.43	Marufuzzaman, Ekşioğlu and Hernandez (2015)
Trucker wage (SAR per month)	1,500	KAPSARC assumption
Number of truckers (people per route)	6	KAPSARC assumption
Number of trips per month per route	80	KAPSARC assumption
Maritime performance and cost		
Production tanker rate ($ per day)	8,400	KAPSARC assumption
Production tanker dead weight (thousand tonnes)	50	
Roundtrip (days)	4	
Average ship speed (knots)	12	Adland et al (2020)

Note: A surcharge of $1 per barrel is applied for new locations that require land. MWh= Megawatthour; SAR= Saudi Arabian riyal.
Source: See table.

Figure A1. Projection of the social cost of carbon dioxide from 2021 to 2040.



Source: KAPSARC estimates based on IPCC (2018).

Endnotes

[1] This type of bottom-up approach is common for analyses like ours. For instance, Herran, De La Cruz and de Andres (2010) use a similar optimization method. They assess intraday (i.e., short-term without investment) transport planning for several oil products through a pipeline system. Our study differs from theirs in a few ways. First, our goal is to assess long-term planning. Second, their method assigns integer values to some variables. Third, we include multiple modes of transport. ICF, an advisory group, uses the same optimization approach to analyze the crude oil network in the U.S. and Canada (API 2017). More recently, Wang et al. (2021) assess the distribution of refined oil products using an optimization model with similar constraints to those applied in this study. However, their model also restricts some variables to integer values, whereas our model is purely continuous. Additionally, our model includes additional constraints related to trucking transport and a different objective function, as the subsequent sections explain.

[2] This cost covers material damages, administrative costs, medical costs, and non-monetary costs related to road accidents.

[3] For instance, Saudi Aramco (2018) released information on Saudi refinery fuel production in 2017.

[4] The main file that is run for the model is DistStations.gms. All other files are called within this main file. The file ‘Display.gms’ consists of parameters that are calculated from the resulting model variables. The parameters present figures that are useful for writing reports or as inputs to visualizations. The file ‘distdata.xlsx’ contains data inputs pertaining to the capacities of PBPs, pipelines, and the loading and unloading bays at PBPs. It also includes projected oil price changes and the quantities of each fuel demanded through the horizon of the analysis. All monetary values in the file are said to be in 2020 United States (U.S.) dollars, but that may be changed by the user.

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Notes

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About the Project

The refined products' distribution system model was developed as part of KAPSARC's advisory work. It has taken a similar development path as the KAPSARC Energy Model (KEM). It may be embedded in the KEM's oil refining model or run as a standalone product.

KAPSARC

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