Dynamic Supply Chain Network Design for Diesel Fuel Consumption in Oil and Gas Fields

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Abstract. A dynamic supply chain network (*SCN*) design problem is addressed in this work to optimally fulfill diesel fuel demands in oil and gas fields. Through a novel mixed integer linear programming (*MILP*) formulation we seek to determine the location of a group of storage tanks (*ST*) aiming to fulfill the diesel fuel demand while minimizing the net present value of the overall costs over the planning horizon. We introduce the concept of by the *mobile ST*, which can be seized of released at any period during the planning horizon. *Mobile STs* can be moved period by period among the grid of potential nodes of the superstructure. An integrated *SCN* is considered, taking into account all its distinctive characteristics. In fact, a generalized approach is developed allowing for flexible flows across the network, capturing the intertwined nature of decisions. Economies of scale governing capital investments and operational costs are reflected in terms of the different types of *ST* to be optimally selected by the model. Lastly, the service level is assessed through a hybrid indicator composed of the magnitude of the flows and the total time required to fulfill fuel demands. A case study under different scenarios is addressed to show the potentials of the proposed approach and the efficiency of the *SCN* designs being obtained.

Keywords: dynamic, supply chain, design, optimization, diesel fuel

1 Introduction

A supply chain is a network of facilities comprising of manufacturing plants, warehouses and distribution centers, which performs a wide range of operations with the aim of fulfilling the demand of certain products/services (final or intermediate) during the planning horizon [1]. Designing a supply chain network (*SCN*) implies to make decisions on the location and the type of facilities to be installed, suppliers selection, products to be stored, inventory policies and transportation modes. The final goal is to supply the products while minimizing the net present value of capital expenditures and operational costs. Furthermore, the network responsiveness should be planned accounting for the service level (*SL*) required by the customers. It is relevant to point out that the *SCN* design involves major capital investments in infrastructure, equipment and management systems, typically facing a long-term payback period. Additionally, the resulting *SCN* does not usually allow for substantial changes and re-designs, which hinders the efficiency of the supply chain operation (*SCO*), as shown by Melo et al. [2]. However, recent works in the area are considering the possibility that certain resources could be relocated or resized. In particular, according to Melo et al. [3], this concept is being applied to the gradual relocation, expansion and/or reduction of storage/production facilities during the planning horizon. Melo et al. [3] indicate that the facility location and distribution network design problems have been studied for many years but an important number of issues have not received adequate attention though. Dynamic relocations, expansions or reductions of storage capacities are among these topics. In the same direction, Barbosa-Póvoa et al. [4] state that a large percentage of the papers (77%) related to the network design problem deal with static models, meaning that the network, after being determined, stays the same during the planning horizon. The rest of the papers (23%) include dynamic or multiperiod features.

In general terms, as remarked by Shah [5], market globalization along with shortening of product life-cycles and the need for high standards of responsiveness challenge modern supply chains to be agile and flexible enough to face a changing environment. As a result, the development of a new *SCN* has become a very important issue. Several works in the related literature address the *SCN* design problem using different approaches and conceptual models, trying to capture all the distinctive characteristics, though many issues still remain open [2,5].

In this work we apply general concepts on the dynamic *SCN* design to the particular problem of the diesel fuel supply to oil and gas fields (*F*). Tavallali et al. [6,7] remark that the intrinsic dynamics of each oil and gas field suggest that the design planning, development, management and operation activities are fully intertwined over a field's life cycle. Also, it is highlighted that the optimal design and planning of oil and gas fields' infrastructure is a highly complex and challenging problem involving many decisions over time. Moreover, in the production of unconventional resources (shale and tight oil and gas) even greater sophistication is required in technologies to achieve cost-efficient exploration, development and exploitation.

1.1 Diesel Fuel Demands in Oil and Gas Fields

Every oil and gas well demands certain amounts of diesel fuel in different refining grades (*DG: G2* and *G3*) to perform the so called upstream operations, from drilling to completion and workover tasks. In the next section, the specific operations requiring *DG* are described. For our particular problem, we assume that a group of diesel storage tanks (*ST*) have to be placed to supply a group of oil and gas fields (*F*). A *ST* is replenished from refineries or major suppliers, and then fulfills diesel requirements from every field *F* allocated to this tank. The *STs* are necessary due to the higher costs paid to reach every punctual demand of every well from the origin points (refineries). Regarding the dynamic nature of the design problem, the aim is to address the asymmetric distribution of the *DG* demand over the planning horizon, mainly due to the intensive drilling of fields in certain periods, and its geographical dispersion. We propose to use *mobile ST* that can be allocated to specific points guaranteeing a better service level in neighboring area. The proposed model can select the number and position of the *mobile STs* at every period, and move them to other locations over the planning horizon.

Furthermore, one of the main weaknesses detected in the literature is the lack of integration of all the *SCN* features, adopting fixed configurations approaches. This means that the final number of echelons in the *SCN* is pre-determined, imposing hard constrains to the model. The latter is being overcome in recent works [8,9] through Generalized-Supply Chain Network (*G-SCN*) design approaches, representing more flexible networks, deciding on the location of various types of facilities in several nodes, assuming non-hierarchical relationships between the facilities, and demand fulfillment from any node in the network, among other features. The potential of the *G-SCN* approaches rely on the ability to simultaneously solve many trade-offs along the structure, leading to more efficient results.

1.2 Contribution

This paper proposes a novel MILP model for the optimization of the diesel *SCN* design problem for oil and gas fields. We develop a *G-SCN* approach that includes all components commonly found in modern supply chains, yielding a comprehensive conceptual model. Economies of scale are captured through the modeling of a set of facility sizes that are able to be installed in any potential location. The main difference between them is given in terms of the min/max flows to be handled. As mentioned earlier, *mobile* storage tanks are proposed with the aim of improving the service level in certain specific fields, being important decision variables their location, seize, movement and release. Fixed costs, unit handling costs and transportation costs are also dependent on the *size* and *type* of *ST* involved. Finally, service level targets are imposed in order to assess the responsiveness of the *SCN*.

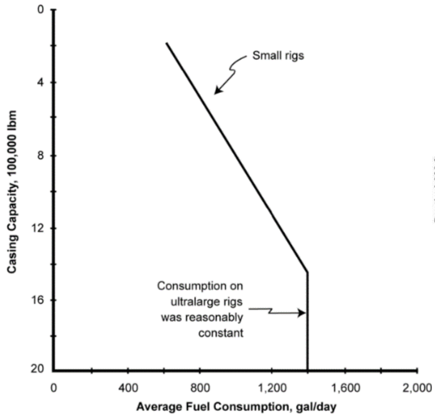
The rest of the work is structured as follows. Section 2 (*Problem Statement*) describes in detail all the problem features and assumptions. Section 3 introduces the proposed mathematical formulation, after which the applicability of the model is proved through the resolution of a case study (Section 4). Lastly, in Section 5, we conclude the work highlighting the main contributions and further research directions.

2 Problem Statement

This work addresses the dynamic *SCN* network design problem for the distribution of two grades of Diesel Fuel (*DG*) required to perform of different operations in oil and gas fields (*F*). The main objective is to determine then optimal number and location of a group of potential *ST* with different characteristics in order to fulfill the *DG* demand of several fields. The first sub-section describes the diesel's demand sources, i.e. all the operations consuming this fuel, distinguishing between grades, rates and other characteristics. The second sub-section introduces the problem statement with all the assumptions made. It is important to highlight the deterministic nature of the data, omitting uncertainty related to demand rates and transportation lead-times.

2.1 Diesel Demand Sources

From the start time of drilling to its normal operation, every well goes under several tasks interventions, many of them requiring fuel to be executed. Among them, the main activities requiring diesel fuel can be classified according to two main sources, (1) rig towers and (2) pumps used to fracture unconventional wells. The first one is the main source for demands of diesel grade 2 (*G2*) and accounts for activities such as drilling, completion workovers, pulling, and maintenance, the last two associated with a frequency of occurrence per period and existing well. The most important operations covered by workovers are the well's completion, replacement of completion components, recovery of old wells, and the conversion from production to injection wells. Likewise, the most relevant tasks performed by pulling operations are the pricking, "fishing", change of broken line pipes and placing new ones [10,11]. There are different *DG* consumption rates depending on the size of the rig tower and the time required for the operation (see Figs. 1a and 1b). All of this can be summarized in the amount of diesel grade *G2* required for every new and existing well in the field. The second main source (2) is composed of several tasks in which the supply of diesel grade *G3* becomes critical for pumps during the stimulation of a new unconventional well. Thus, the demand of fuel (*G3*) can be easily expressed as a volume requirement per new unconventional well. Finally, from the fuel consumption of *G2* and *G3* derived from drilling and fracturing plan, and the number of existing wells at every field, the total demand can be computed for each period in the planning horizon. Even though there are many other activities that entail *G2* and *G3* diesel fuels, the classification adopted yields a valid simplification of the model without setting aside the complexity of the problem. This constitutes a crucial input for the *SCN* design problem to optimally fulfill diesel fuel demands over time.



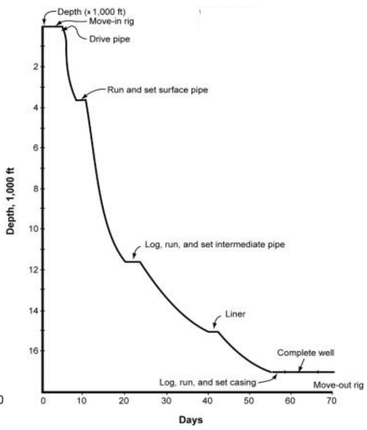


Fig. 1. a) Workover rigs' fuel daily consumption according to the casing capacity [10]. **b)** Drilling duration (in days) depending on the well depth [10].

2.2 Problem Statement and Assumptions

The storage tanks to be installed are categorized in two *types*: *fixed* and *mobile*. *Fixed ST* to be placed among a determined set of potential nodes are of two sizes: *large* or *medium*. In other words, each potential node for *ST*, if selected, has to also adopt one of these facility sizes. Besides, lower and upper bounds are imposed for the flows of every *DG* (*G2* and *G3*) managed by a *ST* according its size. Additionally, lower and upper bounds are set on the total flow of *DG* (*G2+G3*) distributed by every *ST*. Regarding the capital investments in *fixed STs*, they are placed at the beginning of the planning horizon and the facilities are operative since the first period. In contrast, the *mobile ST* can be installed or removed at any period of the planning horizon. Even though these facilities have a notably lower flow capacity compared with the *fixed ST*, this situation may be beneficial when companies are drilling intensively certain fields and need a better service level during a limited period of time. *Mobile STs* are capable of being relocated indefinitely among different potential nodes during the planning horizon. The time expended in the relocation and setup of a *mobile ST* is insignificant compared to the length of the time periods dividing the planning horizon. Then, the minimum permanence established for *mobile ST* in a field is equal to one period of time. In addition, as no stock can be accumulated at the end of each period, *mobile STs* are empty at that moment and can be easily relocated with the appropriate equipment. Installing or removing *mobile STs* requires a specific capital investment in the corresponding period, while the relocation costs are not included explicitly due to its negligible magnitude. It is important to mention that a specific potential node cannot be occupied with both fixed and *mobile ST*.

Operational Costs

Regarding the operational cost of both types of *ST*, a fixed annual maintenance cost is incurred by every operative facility while unit operation costs are added according to the *type* and *size* of the *ST*. The differences between facility sizes aim to capture the economies of scale determining both capital investment and operational costs when the size of the storage tank and the amounts being handled vary. This typically non-linear relationship between the size of a facility and the corresponding cost is such that every additional unit added to the size of a facility is more economic than the previous one. A similar behavior is observed for the unit operational cost, which tends to be smaller for larger *ST* due to the use of more efficient equipment. This is captured by different unit costs for each *type* and *size* of *ST*.

In our model, stock policies are left aside assuming that in this particular case, where the number of products is small, they will not imply hard constrains to the further *SCO*. However, average inventory levels can be obtained after solving the *SCN* design problem by quantifying the number of *ST* being selected, their *type* and *size*.

Fuel Primary Supply

The origin of fuel supplies is a group of existing refineries (*R*) and larger suppliers in the neighboring area of the oil and gas fields. The location of new suppliers is not addressed by this work. Every existing *R* has its own availability of *DG* per period (normally years) in the planning horizon, being a decision variable of the proposed model the selection and definition of amounts to be purchased. It is important to mention that direct supplies from refineries to fields are avoided. Therefore, a minimum of two echelons is imposed to the model, meaning that the fuels have to be stored in at least one *ST* before being delivered for consumption in oil and gas wells.

Once acquired, *DGs* move across certain nodes of the *SCN* until being dispatched to the wells or operation areas. In this particular application of the *SCN* design problem, the number of movements a *DG* makes before being delivered has certain constraints: (1) if the *DG* is supplied to a field from a *fixed ST*, then this *ST* has to be directly supplied from a refinery, and (2) if a well is supplied from a *mobile ST*, this has to be supplied from a *fixed ST* and never directly from a refinery. The situation where inner logistic flows exist between *fixed ST* (of similar or different *sizes*) does not make sense due to the possibility of a direct supply from a refinery, which implies lower costs. Travel distances are shorter (or at most equal), and lesser operations (charge/discharge) are required. Additionally, the second constraint applied to *mobile STs* is due to their reduced size, which hinders the possibility of being supplied with big loads from a refinery. Besides, no single sourcing constraints are imposed, allowing for multiple *ST* to supply a single field. There is no restriction on the type (*fixed/mobile*) or size (*large/medium*) to finally supply a field. Moreover, every location has the potential of sharing its infrastructure to manage both diesel grades, which should be encouraged by the model because of the reduction of fixed costs.

Transportation Costs and Service Level

With regards to the transportation costs, a variable term is computed depending on the *types* of *ST* being linked. This intends to capture the economies of scale relating transportation costs and load sizes. We assume that big tank trucks (40k liters) are used to move the fuels from refineries to *large/medium STs*. The transportation between the latter and *mobile ST* or the final destination, is carried by medium size tank trucks (17k liters). For the former case, big trucks are required because of the full replenishment of the *ST*. Additionally, the main roads being used are usually in better conditions for loads of larger magnitude. Regarding the latter case, medium (even small) tank trucks are required due to the little and less frequent demands of every punctual oil or gas well location into the fields. This leads to remarkably uneven unit transportation costs comparing primary supplies with last-mile distribution.

Finally, targets on the service level (*SL*) are proposed in order to assess the responsiveness of the *SCN*. We develop performance indicator composed of the total time required to serve a well and its corresponding flow. If the target on the *SL* are challenging, extended *SCN* with multiple *mobile ST* are to be obtained, while if the targets are relaxed, the use of *mobile ST* may be not justified.

Problem Statement

In short, the decisions to be made by the *SCN* design optimization model seek to determine: (1) the number of *fixed ST* to install, (2) the size of *fixed ST*, (3) the installation, relocation and release of *mobile ST* per period, (4) the *DG* allocation to *ST*, and (5) the annual flows between nodes ($R \rightarrow ST \rightarrow F$). The proposed formulation integrates a wide range of the main features of a *SCN*, yielding for straightforward transfer of the results to reality. In particular, the main concepts introduced in this work are the flexible relationships between the different nodes in the network, allowing for the total or partial fulfillment of the demand from any *ST*, also capturing the economies of scale determining investment and operational costs of every facility in the network. Besides, the concept of *mobile ST* is presented, creating a dynamic *SCN* design that permits the achievement of higher service level targets for different oil and gas fields, at reduced costs when compared with typical fixed structures. The optimization model simultaneously solves many trade-offs of the problem to finally adopt the best design, minimizing the net present value of the overall costs over the planning horizon.

3 Mathematical Formulation

In order to mathematically represent the problem previously described, a Mixed Integer Linear Programming (*MILP*) formulation is proposed. The aim is to supply a set of fields $J=\{1, 2, \ldots, m\}$ with a group of diesel grades $I=\{1, 2, \ldots, n\}$ over a planning horizon $T=\{1, 2, \ldots, h\}$. Each field has a given geographical position and a specific annual demand $D_{ij\tau}$ (10^3 m^3 or *MMlt*) of i for year τ. The *DG* can be purchased in a set $S=\{1, 2, \ldots, r\}$ of suppliers or refineries with a given geographical position. To fulfill fields' fuel demands, a network of storage tanks (*ST*) has to be installed. A set $A=\{1, 2, \ldots, p\}$ of potential *ST* nodes with their corresponding positions is proposed for the design of the *SCN*. Note that the discrete spatial approach stems from the need to avoid bi-linear terms in the formulation. If a continuous spatial approach were adopted, nonlinearities would appear because of the resulting variable nature of the distance between nodes. Moreover, optimal location on the continuous space may be impractical or not owned by the company. In our model if a node a is selected for a *fixed ST*, the binary variable vf_a takes value one, and zero otherwise. Then, if the selected node is decided to be of size t (*large/medium)* we force the binary variable $w_{a,t}$ to be equal to one (Eq. 1). In short, if the model decides to install a *fixed ST* in node a, it has also to be characterized by its size. Furthermore, when a node a is selected, any fuel i can be allocated to it. The binary variable $q_{i,a}$ takes value one if i is allocated to a, and zero otherwise.

$$\sum_t w_{a,t} = vf_a \quad \forall a \quad ; \quad q_{i,a} \leq vf_a \qquad \forall i, a \tag{1}$$

In addition to regular *ST*, if a *mobile ST* is selected to be placed in the node a, cointaining fuel i in period τ, then the binary variable $vm_{a,i,\tau}$ takes value one and zero otherwise. We note that, in contrast to vf_a, this new binary variable can vary periodically, which implies the multiperiod and dynamic nature of the approach. Unlike *fixed SF*, only one *DG* can be located at the same time (Eq. 2). Furthermore, locating both *fixed* and *mobile ST* in a single node is not allowed by Eq. 2.

$$\sum_i vm_{a,i,\tau} \leq 1 \quad \forall a, \tau \quad ; \quad \sum_i vm_{a,i,\tau} \leq (1 - vf_a) \quad \forall a, \tau \tag{2}$$

The overall capacity of a *ST* is related with the number of tank trucks that can be dispatched per day. It is assumed that the allocation of fuel *i* to a certain *fixed ST* of size *t* forces to handle at least a minimum amount ($qf_{i,t}^{lo}$) during every period. Additionally, it is imposed a maximum volume ($qf_{i,t}^{up}$) also depending on the size *t* of the *ST.* Similar constraints are imposed to the overall flows that justify the installation of a *SF* of size *t*. Due to its separate modelling, *mobile ST* have independent parameters for these capacity bounds, namely $qm_{i,t}^{lo}$ and $qm_{i,t}^{up}$. Eq. 3 establishes effective bounds according to the size of a *fixed ST,* and Eq. 4 determines the corresponding overall bounds. Binary variable $wq_{i,a,t}$ takes value one when $w_{a,t}$ and $q_{i,a}$ are both active, and zero otherwise (Eq. 5). Bounds on the flows of *mobile SFs* are modelled by Eq. 6.

$$\sum_t qf_{i,t}^{lo}\, wq_{i,a,t} \le QA_{i,a,\tau} \le \sum_t qf_{i,t}^{up}\, wq_{i,a,t} \quad \forall\, a, i, \tau \tag{3}$$

$$\sum_t tq_t^{lo}\; w_{a,t} \le QT_{a,\tau} \le \sum_t tq_t^{up} w_{a,t} \quad \forall\, a, i, \tau \tag{4}$$

$$wq_{i,a,t} \le w_{a,t} \;\; ; \; wq_{i,a,t} \le q_{i,a} \;\; ; \; wq_{i,a,t} \ge q_{i,a} + w_{a,t} - 1 \quad \forall\, i, a, t \tag{5}$$

$$\sum_t qm_{i,t}^{lo} vm_{a,i,\tau} \le \sum_j QMJ_{i,a,j,\tau} \le \sum_t qm_{i,t}^{up} vm_{a,i,\tau} \quad \forall\, a, i, \tau \tag{6}$$

In order to fulfill the fuel demand at every field, the positive variables $QAJ_{i,a,j,\tau}$ and $QMJ_{i,a,j,\tau}$ account for the annual flows of *i* to *j* from a *fixed* or a *mobile ST*, respectively. The total flows towards a demand node have to be equal to its corresponding demand (Eq. 7). No limitations are imposed on the *size* or *type* of *ST* serving oil and gas wells, thus allowing the model to select larger or smaller locations, near or far away. Also note the multi-sourcing possibility and that it is not allowed to deliver a fuel directly from a refinery, meaning that every field must be supplied just from *STs*, establishing a minimum of two echelons to reach the demand points.

$$D_{i,j,\tau} = \sum_a QAJ_{i,a,j,\tau} + \sum_a QMJ_{i,a,j,\tau} \qquad \forall\, i, j, \tau \tag{7}$$

Other flows complete the movements within the *SCN*, basically the primary logistics (the flows from refineries to *STs)* and inner logistics (the flows between a pair of *STs*). As explained in the previous section, no inner flows are allowed between *fixed STs* and secondly, *mobile STs* can only be supplied from *STs* (not from refineries). The variable $QRA_{i,r,a,\tau}$ represents the annual amount of *i* purchased to *r* and shipped to *a*. Similarly, $QAA_{i,a',a,\tau}$ is the flow of *i* from *a'* to *a* during year τ, being *a'* a *fixed ST* and *a* a *mobile ST*. Eq. 8 computes the annual flow $QA_{i,a,\tau}$ of *i* moving across *a* and the annual overall flow $QT_{a,\tau}$. On the other hand, it is critical to ensure the volume-balance for each active *ST*, guaranteeing that the incoming flows are equal to the outgoing flow, either to other *STs* or to fields. Volume balances are given by Eqs. 9 and 10 for *fixed* and *mobile STs*, respectively.

$$QA_{i,a,\tau} = \sum_i QRA_{i,s,a,\tau} \quad \forall\, i, a, \tau \quad ; \quad QT_{a,\tau} = \sum_i QA_{i,a,\tau} \quad \forall\, a, \tau \tag{8}$$

$$QA_{i,a,\tau} = \sum_{a' \neq a} QAA_{i,a,a',\tau} + \sum_j QAJ_{i,a,j,\tau} \quad \forall\, a, i, \tau \tag{9}$$

$$\sum_{a' \neq a} QAA_{i,a',a,\tau} = \sum_{j} QMJ_{i,a,j,\tau} \quad \forall\, a, i, \tau \tag{10}$$

Note that the *SCN* is assumed to operate under steady-state conditions, without stock accumulation between subsequent periods. Following a similar logic, the decision of purchasing a fuel from a specific refinery is made by the binary variable $vp_{i,r}$. A minimum annual flow $qp_{i,r}^{lo}$ is imposed if refinery supply is active. The maximum availability $qp_{i,r}^{up}$ of every fuel at every refinery has to be also accounted for (Eq. 11).

$$qp_{i,r}^{lo}.\,vp_{i,r} \;\leq \sum_{a} QRA_{i,r,a,\tau} \leq\; qp_{i,r}^{up}.\,vp_{i,r} \quad \forall\, r, i, \tau \tag{11}$$

In order to relate the binary variables (vf_a, $vm_{a,i,\tau}$ and $q_{i,a}$) with their corresponding flows, Eqs. 12 and 13 are presented.

$$QAJ_{i,a,j,\tau} \leq D_{i,j,\tau}.\,vf_a \quad ; \quad QAJ_{i,a,j,\tau} \leq D_{i,j,\tau}.\,q_{i,a,\tau} \quad \forall i, a, j, \tau \tag{12}$$

$$QMJ_{i,a,j,\tau} \leq D_{i,j,\tau}.\,vm_{i,a,\tau} \quad \forall i, a, j, \tau \tag{13}$$

To determine the links between different types of nodes, new binary variables are used: (1) $zf_{i,a,j,\tau}$ is equal to one if the *fixed ST* in node *a* supplies field *j* with *i* during τ, and (2) $zm_{i,a,j,\tau}$ is equal to one if a *mobile ST* in node *a* supplies *j* with *i* during τ. These binary variables are related with the previous through Eqs. 14 and 15, and determine the value of other positive variables through Eqs. 16, 17 and 18. In all cases *M* is a large enough positive number (for instance, M=$\max_{\tau,i}\left\{\sum_j D_{i,j,\tau}\right\}$).

$$zm_{i,a,j,\tau} \leq vm_{a,i,\tau} \qquad \forall\, i, a, j, \tau \tag{14}$$

$$zf_{i,a,j,\tau} \leq vf_a \;\; ; \;\; zf_{i,a,j,\tau} \leq\; q_{i,a} \qquad \forall i, a, j, \tau \tag{15}$$

$$QAJ_{i,a,j,\tau} \leq D_{i,j,\tau}.\,zf_{i,a,j,\tau} \quad \forall i, a, j, \tau \tag{16}$$

$$QMJ_{i,a,j,\tau} \leq D_{i,j,\tau}.\,zm_{i,a,j,\tau} \quad \forall i, a, j, \tau \tag{17}$$

$$QAA_{i,a',a,\tau} \leq M.\,vm_{a,i,\tau} \quad ; \quad QAA_{i,a',a,\tau} \leq M.\,vf_{a'} \quad \forall\, i, a, a', \tau \tag{18}$$

In our model, it is important to track the total number of active *mobile STs* (Am_τ) in order to record the seizing, relocation and releasing of *STs* over the planning horizon. This is essential to compute the capital investment on new infrastructure. Eq. 19 presents the balance of *mobile ST* where the positive variables Om_τ and Cm_τ accounts for the number of seized and released *ST* per period, respectively. The relation of Am_τ with the binary variable $vm_{a,i,\tau}$ deciding on *mobile STs* location is described by Eq. 20.

$$Am_\tau = \; Am_{\tau-1} + \; Om_\tau - \; Cm_\tau \quad \forall\, \tau \tag{19}$$

$$Am_\tau = \sum_{a} \sum_{i} vm_{a,i,\tau} \qquad \forall\, a, i, \tau \tag{20}$$

Economic Objective Function

To end up with an accurate formulation it is critical to account for both operational and capital investment costs in an integral study of the *SCN*. As it was mentioned earlier, the installation of *fixed STs* is placed at the beginning of the planning horizon, and If_t is the capital expenditure required to build a *ST* of size *t*. In the case of *mobile STs*, *Im* and *Cim* account for the capital expenditure in the acquisition of new *mobile* *tanks* and in the release of existing ones, respectively. The capital expenditure in *fixed* (*CEF*) and *mobile STs* (CEM_τ) is computed by Eq. 21. Besides, the annual purchase cost TPC_τ is obtained through Eq. 22, being $cp_{i,r}$ the unit cost of fuel *i* from refinery *r*.

$$CEF = \sum_a \sum_t If_t \,.\, w_{a,t} \;\; ; \;\; CEM_\tau = Om_\tau . Im + Cm_\tau . Cim \quad \forall \tau \tag{21}$$

$$TPC_\tau = \sum_a \sum_i \sum_r QRA_{i,r,a,\tau} . cp_{i,r} \quad \forall \tau \tag{22}$$

Annual fixed costs (accounting for maintenance and administrative expenditures) are charged in every *fixed ST* installed, according to its *size* (fcf_t). In turn, *mobile STs* pay an annual fixed cost given by *fcm*. In fact, large *fixed STs* pay higher fixed costs, but can manage a much larger flow. Eq. 23 computes the total annual fixed cost TFC_τ.

$$TFC_\tau = \sum_a \sum_t fcf_t . w_{a,t} \; + \; Am_\tau . fcm \quad \forall \tau \tag{23}$$

Regarding the unit operational costs, we assume a dependence on the *ST type* and *size* in order to capture the economies of scale. Unit operational costs are larger as the *size* of the facility is reduced. A unit operational cost ocf_t or *ocm* is incurred for managing one unit of fuel *i* in a *fixed SF* of *size t* or in a *mobile ST*, respectively. Then, the total annual operational cost (TOC_τ) can be readily obtained by Eqs. 24 and 25.

$$TOC_\tau = \sum_a \sum_i \sum_t QAT_{i,a,t,\tau} . ocf_t \; + \; QMJ_{i,a,j,\tau} . omc \quad \forall \tau \tag{24}$$

$$\sum_t QAT_{i,a,t,\tau} = QA_{i,a,\tau} \quad ; \quad QAT_{i,a,t,\tau} \le qf_{i,t}^{up} . w_{a,t} \quad \forall i, a, t, \tau \tag{25}$$

The transportation cost depends on the type of nodes being linked. Particularly, *vtc1* accounts for the unit transportation cost (U$S/km.lt) between a refinery and a *fixed ST*, *vtc2* for the inner flows between *fixed* and *mobile STs*, and *vtc3* is the unit transportation cost to finally supply a demand point. In this work, *vtc3* is much larger than *vtc2* and *vtc1* due to the notably smaller capacity of the tank trucks supplying oil and gas fields and the worse conditions of the roads. The distances between nodes are computed by the euclidean norm, introducing a tortuosity factor to reflect the perfect roads inexistence. The total annual transportation cost TTC_τ is given by Eqs 26 to 29.

$$TTC_\tau = TTC1_\tau + TTC2_\tau + TTC3_\tau \tag{26}$$

$$TTC1_\tau = \sum_r \sum_a \sum_i Dist_{r,a} . vtc1 . QRA_{i,r,a,\tau} \tag{27}$$

$$TTC2_\tau = \sum_a \sum_{a'} \sum_i Dist_{a,a'} . vtc2 . \; QAA_{i,a,a',\tau} \tag{28}$$

$$TTC3_\tau = \sum_a \sum_j \sum_i Dist_{a,j} . vtc3 . (QAJ_{i,a,j,\tau} + QMJ_{i,a,j,\tau}) \tag{29}$$

The responsiveness of the *SCN* is assessed through the definition of targets on the service level (*SL*) which are composed of the total time required to fulfill a demand point and the corresponding magnitude of the flow. The flow time across the *SCN* is equal to the total transportation time. As the distances and the mean velocity of trucks are assumed to be known, then the lead time to link two nodes ($LT_{a,j}$) can be readily obtained. Eq. 30 accounts for the *SL* target constraint, where the parameter $Demp_{i,j}$ is the average demand of fuel *i* in the field *j* ($Demp_{i,j} = \frac{1}{h} \sum_\tau D_{i,j,\tau}$), and *TT* is the *target* *time* adopted. This equation intends to impose a higher *SL* (lower $LT_{a,j}$) during periods of intensive consumption (higher flows with regards to the average demand).

$$\left(QMJ_{i,a,j,\tau} + QAJ_{i,a,j,\tau}\right)LT_{a,j} \leq Demp_{i,j}\, TT \quad \forall i,a,j,\tau \tag{30}$$

The *SCN* must be designed with the aim of minimizing the net present value of the overall costs (*NPC*, Eq. 31), involving all the discounted cash flows (capital investment and operational costs), at the rate φ during the planning horizon.

$$Min \quad NPC = CEF + \sum_{\tau} \frac{(CEM_\tau + TPC_\tau + TTC_\tau + TFC_\tau + TOC_\tau)}{(1+\varphi)^{\tau-1}} \tag{31}$$

4 Results and Discussion

We address an illustrative case study comprising different demand patterns for every field (see Fig. 2) and increasing services level targets to assess the potentials of the proposed approach. It is expected to obtain a *SCN* able face periods of peak demands very efficiently while having a quick response to farther fields, all of this by exploiting the benefits of *dynamic STs* locations. The total number of *fixed ST* that can be installed has been restricted up to three, based on typical budget constraints. Table 1 displays the main parameters used in the model. The differences among the three scenarios lie on the higher Target Times proposed. In this illustrative case study, the number of fields is *10*, equal to the number of potentials nodes to design the *SCN*.

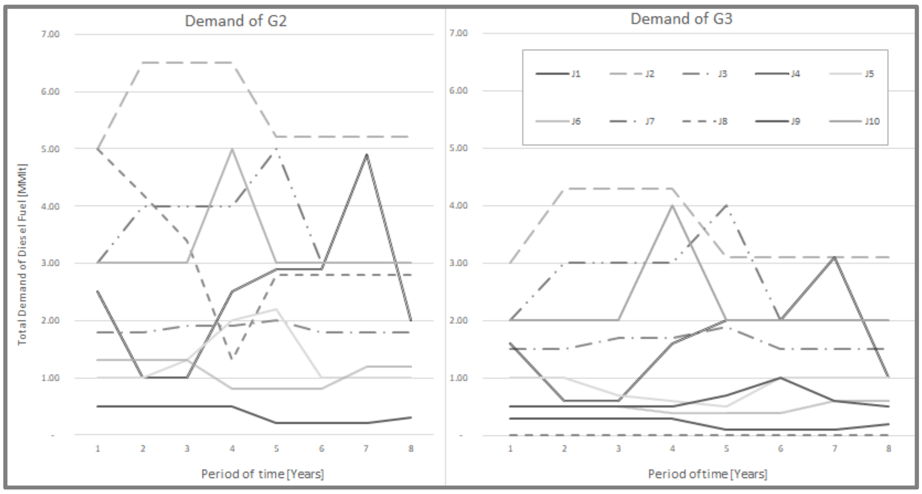


Fig. 2. Demand patterns over the planning horizon for every *F* and *DG*.

The first scenario is proposed to show that a *static SCN* structure is preferred (see Fig. 3) if the pressure on the service level vanishes ($TT \rightarrow \infty$). Observe that no changes on the network design are suggested over the planning horizon, and that only one *mobile ST* is placed in one of the nodes, taking advantage of the lower inner transportation costs. The next two scenarios seek to demonstrate the advantages of the dynamic arrangements within the *SCN* when higher service levels are imposed. Table 2 summarizes the optimal solutions found for each scenario.

Table 1. Case study parameters used in each scenario.

ST Type	If_t [MMUS$]	Costs: fcf_t [MMUS$/Year]	Costs: ocf_t [MMUS$.MMlt/Year]	Capacity [MMlt/Year] tq_{it}^{lo} / tq_{it}^{up}	Transportation Costs [MMUS$]		Scenario	TT [hs]
Fixed Large	*0.58*	*0.22*	*0.04*	*20/36*	*vtc1*	*660*	***1***	∞
Fixed Medium	*0.43*	*0.14*	*0.05*	*7.5/21.5*	*vtc2*	*660*	***2***	*2*
Mobile	***Im / Cim***	***Fcm***	***ocm***	$qm_{it}^{lo}/qm_{it}^{up}$	*vtc3*	*1320*	***3***	*1.2*
	0.15/0.03	*0.09*	*0.07*	*0.05/9*				

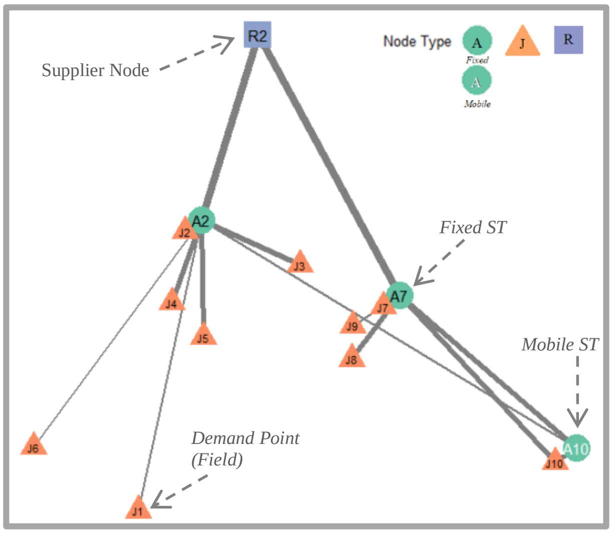


Fig. 3. SCN design for the first scenario.

Table 2. Case study results, cost components (MM USD) and solution statistics.

Scenario	1	2	3	Real World
Nº Large/Medium/Mobile ST	1 / 1/ 1	0 / 3 / 2	0 / 3 / 6	2 / 2 / 9
NPC / TI	38.89 / 1.35	40.13 / 1.61	71.8 / 2.22	714 / 3.41
TFC_τ / TOC_τ	2.3 / 9.61	3.23 / 9.84	5.53 /23.67	24.7 / 6.88
TTC_τ	30.25	29.76	54	169.76
Equations	43,210	43,210	43,210	960,323
Positive/Integer Variables	37,515/8,534	37,515/8,534	37,515/8,534	559,301/191,184
CPU Time (s)/GAP (%)	5.48/0	32.19/0	33.61/0	16,826 / 6

In the second scenario (see Fig. 4), it is worth note that a *large ST* in scenario 1 is converted into a *medium*-size *ST*. This demonstrates that the distribution is now being performed among more *STs* in order to achieve more stringent *SLs*. Conversely, the benefits of the *economies of scale* associated with a *large ST* cannot be fully exploited. A total of two *mobile STs* are used and relocated in different periods. Note that the network structure changes in year 5 driven by specific picks on the fuel demands.

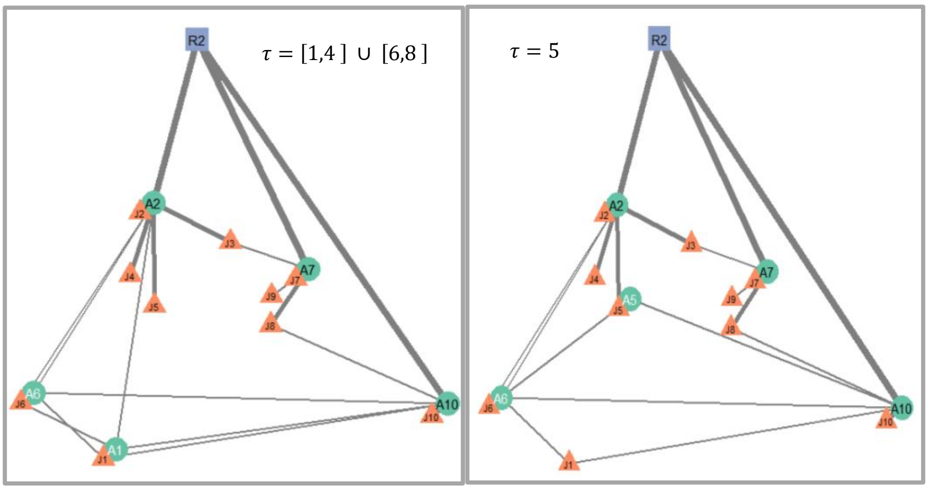


Fig. 4. *SCN* design for the second scenario depending on the period of the planning horizon.

In the third scenario, the total number of *fixed STs* remains equal, while the number of *mobile STs* is three times the number used in scenario 2. This means that certain fields have become much more significant when a faster response is required (lower *TT*), thus making necessary the location of more *mobile STs.* Table 3 shows the seizing and relocation of *mobile STs* over the network during the planning horizon.

Table 3. Location of *mobile ST* during the planning horizon for each *F*. A value one represents the existence of a *mobile ST* in the corresponding potential node.

Node	**DG / Period→**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A2	Grade 2	1	1	1	1	1	1	1	1
A3	Grade 2	1	1	1	1			1	1
A4	Grade 3	1	1	1	1	1	1	1	1
A5	Grade 2	1		1	1	1	1	1	1
A7	Grade 2		1		1	1	1		
A7	Grade 3	1		1				1	1
A8	Grade 2	1	1	1		1	1	1	1
A9	Grade 3		1		1	1	1		
	Total	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**

Finally, the proposed model is applied to a real-world problem with larger numbers of fields and potential nodes in the network (74 in both cases). The resulting model comprises more than 550k continuous variables, 190k binary variables and 960k equations. It takes almost five hours of CPU time to get a solution with 6% of relative gap. The formulation was coded for all cases in GAMS 24.7 and solved using CPLEX 12.6 on an Intel Xeon X5650 with 2.67 GHz CPU and 24GB RAM.

5 Conclusions

We have presented a novel MILP formulation for the optimal design of the diesel fuel Supply Chain Network (*SCN*) serving upstream operations in oil and gas fields. An integrated model is obtained by taking into account all the distinctive characteristics of modern distribution networks, yielding a generalized approach that avoids predefined network structures. The novelties introduced in this work consist on: (1) using *mobile Storage Tanks* (*ST*) yielding a *dynamic SCN* design problem with the aim of facing intrinsic instabilities of the demand patterns and the asymmetric geographical distribution of the fields; and (2) capturing economies of scale governing capital investment and operational costs by proposing *ST* of different *type* and *size*. The MILP mathematical formulation permits to obtain efficient *SCN* designs with different types of *ST* installed at different nodes, according to the relative importance of transportation, capital investment and operational costs, along with the corresponding service level targets being imposed. Results show that the *SCN* configurations effectively solve critical trade-offs along the supply chain structure. Future work will focus on the development of more efficient solution strategies to apply this model to larger case studies and other industrial-size problems.

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