Trends in Energy Markets and Systems: The Case of Natural Gas and Facility Location Techniques

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Abstract. The energy industries development have faced import challenges over time: ensuring high standards of security, promoting efficiency and protecting the environment. Natural gas has become the preferred fuel in the energy market, because of its long-term source and its economic and environment benefits.

Following the steps of electricity, the natural gas market has undertaken its own restructuring process within the context of the European gas directive. The development of natural gas market has been guided by a focus on specific national gas policies, determined by each country's access position to gas reserves.

Because of the strong growth in demand and the Europe's import dependency, countries have been creating and reinforcing marine terminals and storage facilities infrastructures, which constitute the source points of the natural gas network.

The right place to locate these facilities on a network is a locational decision-making issue. One of the most popular models in the facility location literature is the *p*-median model. Our research goal includes this issue, combining physical characteristics of potential locations with economics aspects.

This article analyses the recent changes in the European natural gas market and addresses the research issue of discrete location problems applied to gas networks.

Key Words: Natural gas (NG) market, gas loadflow, liquefied natural gas (LNG), facility location, p-median problem

I. Introduction

About one quarter of Europe´s primary energy consumption is based on natural gas. This fuel incorporates highly important national interests, in terms of economy and social welfare. In gas producing countries, natural gas reserves are considered a national asset and have been exploited for the national benefit. For gas consuming countries, access to gas resources is also of crucial importance. The development of natural gas markets in Europe has so far been guided by national policies that take into account each country's access position to gas reserves.

The gas industry across Europe is developing new pipelines and connections to extend the gas network and thus satisfy increasing demands of European load centers. With the transport and distribution pipelines widespread, the gas demand in other sectors, such as industrial, commercial, residential and transport sector, is growing fast. In Portugal, like in other countries, natural gas steadily increased as fuel in the thermal-based power generation systems and district heating.

Because of its import dependency and expected strong growth in demand, continental Europe gas industry faces important challenges and opportunities [1]. The growth of the European natural gas market will depend, to a large extent, of gas price competitiveness as compared to other energy sources and technologies.

Unlike electricity, natural gas can be stored. However, storage facilities require specific physical characteristics which are difficult to meet. Consequently, it is of major interest to carefully plan the most adequate location for these facilities, minimizing expenses and maximizing throughput and security of supply, observing regulatory, technical and safety restrictions.

Because of its useful applications, discrete network location is an important subfield within the broad field of optimization. The implementation of the strategic points of a natural gas network – supply terminals, transport and storage infrastructures, needs to deal with location issues, using solution techniques that can vary from combinatorial procedures to analytical techniques, including simulation, to automatically analyze different feasible scenarios.

II. NG Industry Characteristics

A. The Technical Infrastucture of the Gas Chain

A complex infrastructure, including upstream and downstream activities, is necessary to comply with the incremental natural gas demand. The production, supply, transmission and distribution are the main activities in the gas chain, which are complementary, technically as well as economically (see figure 1). Strict coordination of such activities is therefore of paramount importance to safeguard high quality supply of natural gas from a technical point of view.

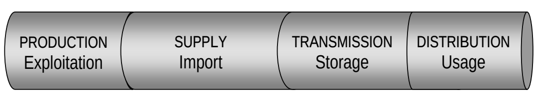

Figure 1 – Natural Gas Chain

Production activity is found only in countries that have gas fields. The exploitation of gas fields is far from easy, but the similarity of the extraction process with oil's has allowed the development of effective technologies and techniques to locate and explore gas reserves. While only a few countries actually have production capacity, most countries rely on security of supply provided by a pipeline network that connects to production fields. This supply method is feasible if the gas production fields are located sufficiently close to consumers, otherwise gas is transported in the liquid form (liquified natural gas - LNG) in ships and delivered to marine terminals or storage facilities. In this case, natural gas is later transported in the gas form through a pipeline to demand centers or directly to end consumers. The distribution activity includes the exploitation, maintenance and development of pipeline infrastructures to supply customers in a local basis.

B. LNG Systems and Uses

LNG is a natural gas that has been cooled to about minus 260 degrees Fahrenheit for shipment and/or storage as a liquid. LNG is more compact than the gaseous equivalent with a volumetric difference of approximately 610 to 1. Liquefaction provides the opportunity to store large quantities of gas for use according to the demand periods. Current LNG facilities reflect different applications of LNG-related technology: marine terminals receive ship delivered imports of LNG and have on-site storage (non producer countries), underground storage facilities and other operations to serve demand [2].
Typically, the LNG is stored until it can be regasified and injected into the pipeline grid. Therefore, LNG facilities constitute the main source of supply for a natural gas network.

An important feature of these facilities is that they provide reliability to their distribution system and operational flexibility during times of high demand. Usually, the transportation pipeline companies also own and operate LNG facilities in much the same way as they own and operate underground storage facilities as part of their integrated systems.
Growth in the use of LNG technology by natural gas industry depends on expansion of current facilities and new construction. The need for additional supply sources to meet projected demand and their optimal location on the gas network is a major issue of our present research.

C. Economic Models

Some differences on the national responses to the emerging EU gas market liberalization can be found. A point of departure is the obvious difference among European countries with respect to access to gas resources. One can distinguish two different models for gas market development: a public property focused model and a public utility focused model [3]. The first model is usually found in countries with voluminous gas fields, and the second model, in countries without gas fields.

Only a few European countries have gas reserves voluminous enough to allow for both domestic consumption and export. In these countries gas reserves are considered as national assets and have been exploited for the national benefit, with the ambition to capitalize economic value. This became a guiding principle in the exploitation of gas resources. The organization of markets based on a public property model focuses in the upstream activities – production and transmission, controlling access to a limited number of players, and the ownership structure is public dominant. This model assures maximization of state revenues and pursues the national welfare and prosperity.

Net importing countries - those without significant gas reserves - have concentrated on gas consumption and gas demand. Policy for the public utility model draws on the idea that natural gas is a vital national energy resource that should be available nationwide. In this regard, the state takes an active role in developing the utility-oriented gas market for economic and political reasons. State control and monopoly regulation was meant to reduce investment risk and to ascertain long-term domestic consumption by developing a domestic consumer market. The public utility model is therefore consumer oriented and heavily relies on specific regulation. Unlike the public property model, it focuses in the downstream activities, also controlling the access to a limited number of actors. As a consequence, the model pursues reasonable consumer tariffs and selective services.

In addition to these two models, there is what one could name a *commodity* focused model, referring to a gas market where natural gas is perceived as a freely tradable commodity – reflecting the ideal of a competition-based gas market. This commodity-oriented model is now challenging all European countries due to the EU gas Directive, 2003/55/CE [4]. Liberalization has affected the image and perception of natural gas, which can no longer be considered only as a public property or a public utility. The ownership structure is open to private dominance. So far, the commodity-based model can be found, to some extent, in the British gas market, where some competition requirements are met. To be able to perform, a commodity based model requires both international and national matured upstream and downstream gas systems.

III. Gas Network Modeling

A typical gas network consists of gas sources (gas producers and storage), gas loads (electric generators, industrial consumers and distribution companies), pipelines (represented by arcs) and the interconnection points of pipelines (nodes). The elements of a pipeline can include a series of devices like compressors, valves and regulators. The compressors are installed in the network to establish the gas pressure so that the gas can flow through the pipeline to the points where it is consumed. Valves and regulators are devices that allow selected sections of the gas network to be cut off and they also provide control of the gas flow rate, prevent excessive growth of pressure in the network and prevent the flow of gas in an undesirable direction.

A directed graph is an efficient way to represent a gas network (see the example of figure 3).

During the almost two centuries that the NG industry has been in existence, there has always been a need for workable equations to relate the flow of gas through a pipe to the properties of both the pipe and the gas, and to the operating conditions such as pressure and temperature. The usefulness of such equations is obvious: systems must be designed and operated with full knowledge of what pressures will result from required flow rates.

A. The Fundamental Equation

Almost every text on fluid mechanics contains some derivation of the fundamental equation governing one dimensional, compressible fluid flow. Excellent derivations are presented in papers referenced in the bibliography [5].

Essentially, one begins with the partial differential equations of motion along with the equation of state and then starts assuming and integrating. The end result for flow in a horizontal pipe is the following equation:

$$Q = C\frac{T_b}{P_b}D^{25}e\left(\frac{P_1^2 - P_2^2}{LGT_aZ_af}\right)^{5} \qquad (1)$$

where:

- C Constant, 77.54(English units);0.0011493 (metric)
- D Pipe diameter (mm)
- e Pipe efficiency (dimensionless)
- f Darcy-Weisbach friction factor (dimensionless)
- G Gas specific gravity (dimensionless)
- L Pipe length (km)
- P_b Pressure base (kilopascal)
- P_1 Inlet pressure (kilopascal)
- P_2 Outlet pressure (kilopascal)
- Q Flow rate (m^3/day)
- T_a Average temperature (K)
- T_b Temperature base (°)
- Z_a Compressibility factor (dimensionless)

This is the fundamental flow equation which is universally accepted as the full and complete statement of how fluid flow works. It shows clearly how flow varies with the pertinent parameters.

B. Loadflow Problem Statement

Whenever significant changes in gas demand or supply are expected to occur, a gas loadflow analysis is needed to see whether the network has enough capability to carry the gas changes while satisfying various network constraints, such as pressure and gas velocity limits at every element of the grid. Details of the flow simulation in gas networks are presented in Osiadacz´s work [6].

The problem of simulation of gas network in steady state, known as loadflow, is usually that of computing the values of nodes pressure and flow rates in the individual pipes for known values of source pressures and of gas injections in all other nodes.

If we look at equation (1) we realize that the total system of equation representing the behavior of pipe network is a non-linear problem. To solve such kind of problem of realistic size in a reasonable amount of time, we need to find effective heuristics methods [7].

IV. Facility Location

An important aspect of optimizing natural gas systems operations is the task of locating source facilities – underground storage or LNG terminals – in the network in their optimal location, in order to make the organization more efficient and profitable. Location decisions are often strategic in nature, that is, they involve large sums of capital resources and their economic effects are long run.

Mathematical location models are designed to address a number of questions including:

i. How many facilities should be sited?
ii. Where should each facility be located?
iii. How large should each facility be?
iv. How should demand be allocated to the facilities' service?

The answers to these questions depend intimately on the context in which the location problem is being solved and his underlying objectives. Generally, modeling location problems requires an understanding of the real world operations that are to be reflected in the model. The purpose of modeling is to identify the tradeoffs between the objectives while capturing as much of the richness of the real world problem as is necessary to ensure the credibility of the modeler and the model itself.

Finally, location models are application specific. That is, their structural form (the objectives, constraints and variables) is determined by the particular location problem under study. Consequently, there does not exist a general location model that is appropriate for all potential or existing applications, but there are some specific algorithms for the solution of facility location problems in discrete space or network (as far as we know there isn't any specific study for NG network, but a facility location model was studied for electric power generating plants [8]).

In natural gas network planning situation we are concerned with the total gas travel distance between source facilities and demand nodes. Distance, or other measure more or less functionally related to distance (e.g., losses or transport cost, demand satisfaction) is fundamental to such problems.

One classic model to study this problem is the *p*-median model, which finds the locations of *p* facilities on a network to minimize the demand-weighted total distance between demand nodes and the source points to which they are assigned. Here, we assume that facilities should be as close as possible to demand centers. Generally, the benefit (cost) associated with a demand node/facility pair decreases (increases) gradually with the distance between the demand and nearest facility.

The *p*-median problem, due to its mathematical structure is NP-hard (for a discussion of NP hardness, see [9]) and therefore cannot be solved in polynomial time. Even though some problems can be solved by using certain approaches like branch and bound, Dantzig-Wolfe decomposition, lagrangian relaxation and other heuristics with search strategy as described in [10], there is a strong need for heuristic methods for large and realistic *p*-median problems. These kind of problems were studied by Daskin [11] and Drezner [12].

Taking into account such considerations as well as the specific characteristics of natural gas systems, we will adapt the *p*-median model to built an algorithm that will find, in a network, the optimal nodes to locate the source points in order to serve the demand weight at a minimal cost.

A. Formulation and Properties

The *p*-median problem has been studied since the sixties. The problem can be stated as finding the location of a fixed number of *p* facilities on a network so the total cost is minimized.

The first explicit formulation of the *p*-median problem is attributed to Hakimi [13] who not only stated the formulation of the problem but he also proved that optimal locations can always be found at the nodes (his model was applied in the field of telecommunications, more precisely in the location of switching centers on a graph). Hakimi

[13], proved that relaxing the problem to allow facility locations on the arcs of the network would not reduce total travel cost.

The cost of serving demand at nodes is given by the product of the demand at node *i* and the distance between the node and its nearest facility. The integer programming formulation of the *p*-median problem is stated as follows:

$$\text{Minimize} \quad \left\{ Z = \sum_{i=1}^{m}\sum_{j=1}^{n} h_i . d_{ij} . y_{ij} \right\} \qquad (2)$$

subject to:

$$\sum_{j=1}^{n} y_{ij} = 1 \qquad i = 1,\ldots,m \qquad (3)$$

$$\sum_{j=1}^{n} x_j = P \qquad (4)$$

$$y_{ij} - x_j \le 0 \qquad i = 1,\ldots,m;\; j = 1,\ldots,n \qquad (5)$$

$$x_j \in \{0,1\} \qquad j = 1,\ldots,n \qquad (6)$$

$$y_{ij} \in \{0,1\} \qquad i = 1,\ldots,m;\; j = 1,\ldots,n \qquad (7)$$

The inputs are:

- i index of demand points
- m total number of demand points
- j index of potential facility sites
- n total number of potential facility locations
- h_i weight associated to each demand point (demand quantity)
- d_{ij} distance between demand area *i* and potential facility at *j*
- P fixed number of facilities

and the decision variables are:

$$x_j = \begin{cases} 1 & \text{if we want to locate at candidate site } j \\ 0 & \text{if not} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if demands at } i \text{ are served by } j \\ 0 & \text{if not} \end{cases}$$

The objective function (2) minimizes the total demand-weighted distance between each demand node and the nearest facility. Constraint (3) requires that each demand node *i* is assigned to only one facility *j*, constraint (4) states that exactly *P* facilities are to be located, constraint (5) links the location variables (x_j) and the allocation variables (y_{ij}). They state that demands at node *i* can only be assigned to a facility at location *j* (y_{ij}=1) if a facility is located at node *j* (x_j=1). Constraints (6) and (7) are standard integrality conditions. In this formulation it is assumed that all demand points are also potential facility sites (*m*=*n*). The *p*-median formulation given above assumes that facilities are located on the nodes of the network.

B. Optimal Solutions

The assumption that the potential facilities sites are nodes on the network limits the number of alternative solutions that must be examined to find a solution to

$$\binom{N}{P} = \frac{N!}{P!(N-P)!}$$

Where *N* is the number of nodes and *P* is the number of facilities to be located. For *N* = 20 and *P* = 2, $\binom{20}{2}$ = 190 which is an acceptable number of combinations. But, if *N* = 100 and *P* = 15, which can be a realistic network, $\binom{100}{15}$ = 2.5E17.

This is a truly heroic task since evaluating each combination involves finding the closest facility to each of the 85 demand nodes at which a facility is not located. As we can see, for even moderate values of *N* and *P* the number of possible solutions that must be enumerated becomes exceptionally large.

We need to find effective heuristic algorithms if we want to solve problems of realistic size in a reasonable amount of time as we propose bellow.

C. Algorithm for P-Median Problem

In this work we propose a construction algorithm in which we attempt to build a good solution.

If we were to locate only a single facility on the network, we could easily find the optimal location by enumerating all possible locations and choosing the best (i.e., by total enumeration). Specifically, since we know that at least one optimal solution to any *p*-median problem consists of locating only on demand nodes, we could evaluate the 1-median objective function, $Z_j = \sum h_i d_{ij}$, that would result if we locate at demand node *j*, for each demand node. We would then choose the location that results in the smallest value of Z_j. If we only want to locate a single facility, it is clear that this approach would give an optimal solution, since we would have tested each possible location and have chosen the selected node *j*(1)*. This process is repeated, but in each iteration ahead we eliminate the nodes that have been selected. Note that *j*(k)* gives the best location for the k^{th} facility, given the location of the first *k-1* facilities. The algorithm ends when *k* is equal to the number of desirable location facilities (i.e. *k*=*P*).

Figure 2 presents a simple flowchart of this heuristic:

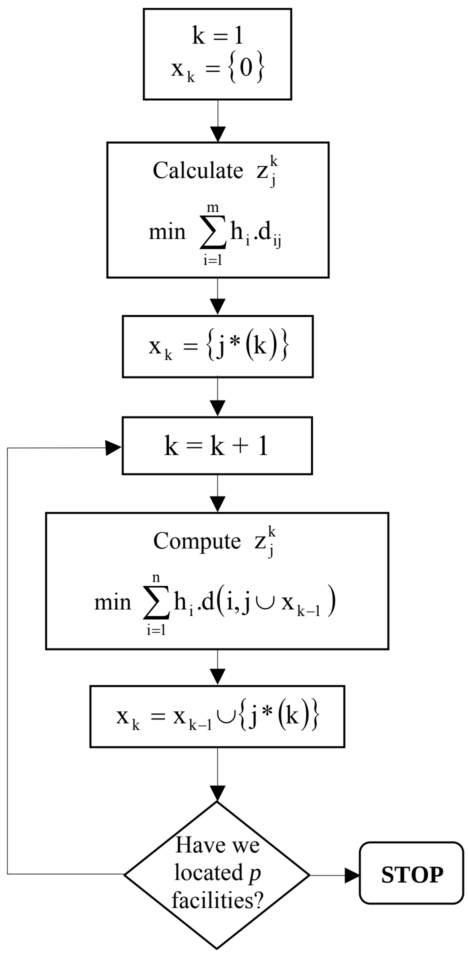

Figure 2 – Heuristic for the *p*-median problem

The solution obtained by this algorithm will not necessarily be optimal, since at each pass we are holding the locations of the first *k-1* facilities fixed. Despite the fact that the solution we obtain in this way may not be optimal, this algorithm is attractive, not only because it is simpler to implement but, in practice, many decisions are made this way. In real gas networks we are often given the location of previous facilities, installed years ago, which cannot be moved. We are then asked to find the location of a few new facilities. If we are only required to locate one additional facility and the existing facilities cannot be relocated, this approach will clearly be optimal.

V. Application Example

To illustrate the approach described above, consider the network shown in figure 3, with four nodes (each identified by its demand in a dashed box), where we want to locate two facilities (P=2).

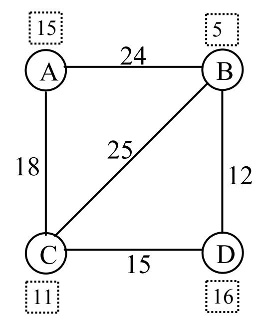

Figure 3 – Sample network for p-median examples

Table 1 gives the matrix $h_i d_{ij}$. By summing the entries in each column we obtain the values of Z_j^1. The smallest Z_j^1 value corresponds to *j*=*C*, with a value of 635. This node is the optimal point to locate the first facility.

Table 1 – Demand times distance for network of fig. 3

	Node *j*			
Node *i*	*A*	*B*	*C*	*D*
A	0	360	270	495
B	120	0	125	60
C	198	275	0	165
D	528	192	240	0
Total	846	827	635	720

To locate a second median, we need to compute $h_i.\min\{d(i,C);d(i,j)\}$ for each node/candidate location pair (*i*,*j*). Table 2 shows the results of this computation.

Table 2 – Computation for second median

	Node *j*			
Node *i*	*A*	*B*	*C*	*D*
A	0	270	270	270
B	120	0	125	60
C	0	0	0	0
D	240	192	240	0
Total	360	462	635	330

Taking into account the column totals which correspond to Z_j^2, we can conclude that it is best to add a facility at node D, with a total demand-weighted distance of 330.

The result shows us that the best nodes to locate the two facilities in that four nodes network are C and D.

VI. Conclusion

The natural gas industry in Europe is currently facing great challenges: harmonizing and balancing the technical operation of each pipeline system and making optimal use of source points location.

The research range in the natural gas industry from the optimization perspective is tremendous. Here, we have introduced only one of the problems in a field that has been recently receiving significant attention – the optimal location of natural gas facilities, using the *p*-median problem.

Because of the computation requisites of such a problem, we outline a heuristic through which we attempt to build a feasible solution, though not necessarily an optimal one. Despite this fact, the respective algorithm is appealing for a number of reasons. Firstly, the requested computational time is largely decreased. Secondly, in practice many decisions are made this way - we are given the location of a certain number of facilities which cannot be displaced and we are then asked to find the location of new facilities (often no more than one or two).

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