Optimal Location of Natural Gas Sources in the Iberian System

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Abstract: - The Iberian Natural Gas system is facing the challenge of strong growth in demand in a transportation gas network isolated from Europe. Depending only by itself, the Iberian gas system needs to carefully decide about the optimal location of its Gas Supply Units – GSUs, minimizing system total cost.
The *p-median* problem is the classical model of locating *P* facilities on a network. In this paper we propose a lagrangean heuristic, an approach to solve the *p-median* problem. This heuristic is applied to the Iberian natural gas system, modelised with 65 demand nodes – 18 Portuguese districts and 47 Spanish provinces.
We present the results obtained for the location problem and the allocation of loads to gas sources, using a 2015 forecast demand scenario.

Key-Words: - Location model, gas supply units - GSUs, *p-median* problem, lagrangean relaxation, subgradiente optimization

1 Introduction

Much of the recent concern about natural gas supplies has been motivated by the great growth in demand. Because of the demand growth patterns and the Europe's import dependency, European countries have been creating marine terminals, storage facilities infrastructures [1] and gas injection points, which constitute the source points of the system, called Gas Supply Units – GSUs.
Despite geological constraints, the location of such infrastructures in network should be carefully planned, in order to minimize overall costs.
The aim of this paper is the presentation of a location model applied to the Iberian high pressure transport gas, a system modelised with 65 demand nodes. For a growing demand scenario forecasted to 2015, we will study the optimal GSUs location on the gas network, minimising expenses and maximizing throughput and security of supply.
In our model we consider that the best place to locate the GSUs are nodes. Some of these nodes already contain an existing GSU which cannot be relocated.
In literature, we can find different location models [2]. To deal with the realistic gas system, the mathematical models need to be extended, observing regulatory and technical restrictions.

In case of natural gas systems, the choice of location problem is heavily dependent on the network size. For small networks, the fixed charge facility location problems can be used with satisfactory results [3]. For large networks, Beasley [4] describes very effective heuristics dealing with location problems.

The search for *p-median* nodes on a network is a classical location problem that minimizes the sum of all distances from each demand point to its nearest facility. The *p-median* problem, due to its mathematical structure, is NP-hard and therefore cannot be solved in polynomial time. So, it is necessary to use software technologies or heuristics methods for large and realistic *p-median* problems.

To apply this study to the Iberian network, we developed an effective lagrangean heuristic, using lagrangean relaxation and subgradient optimization to solve the dual problem [5].

With our location model, we intend to provide a decision support tool that helps to find the optimal number of GSUs and the right place to locate them. After this task we determine the most efficient allocation from demand points to gas sources, using an exact approach.

In section two we explain how the Iberian gas network was modelised.

Section three outlines an optimization-based approach to solve the *p-median* problem.

The lagrangean relaxation applied to the *p-median* location model was inspired in Lorena works, [8] and [9]. The computational results are presented for the proposed location lagrangean heuristic and the allocation problem. We conclude confirming that this heuristic is an effective locational algorithm if we want to solve problems of realistic size in a reasonable amount of time.

2 Iberian Gas Network Model

The Iberian high pressure (60 bar) natural gas network is defined in terms of sources (GSUs), demand points and junction nodes, that are connected by pipelines.

The Iberian pipeline transport system has an extension of approximately 7500 km and links all the demand points connected in these physical pipes. The 65 demand points are aggregation loads, including electrical producers, distribution gas utilities, industrial, commercial and domestic consumers. These loads are geographically organized in 18 Portuguese districts and 47 Spanish provinces as shown in figure 1.

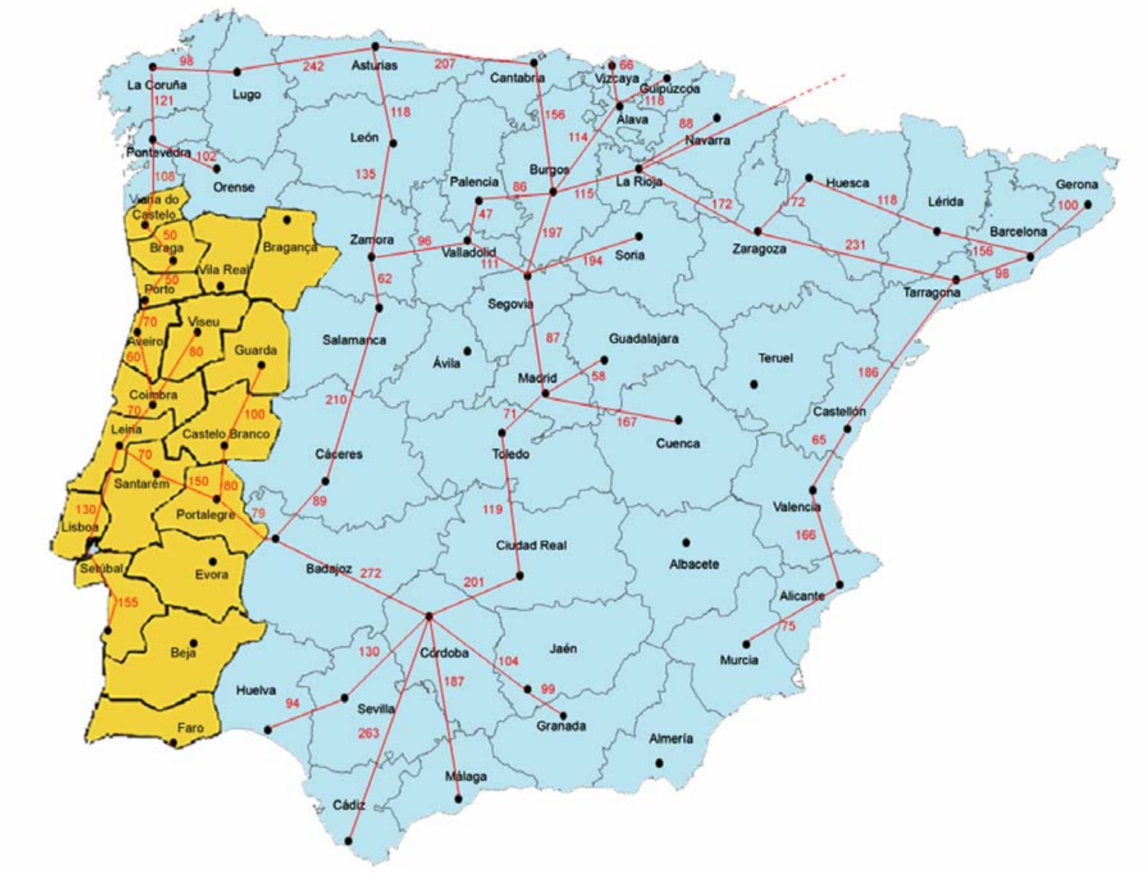

Figure 1: Iberian Natural Gas Pipelines

We can see in figure 1 some demand points which are not connected in the physical pipelines. These are five Portuguese aggregation loads - Vila Real, Bragança, Évora, Beja and Faro, and four Spanish provinces – Ávila, Almaria, Teruel and Albacete. These demand points are supplied by road trucks with gas in liquefied form - the called virtual pipelines. These virtual pipelines are, in fact, every connection between two nodes without a physical pipeline. To avoid design congestion they are not drawn in figure 1.

2.1 Demand Forecast

Analising the current 65 nodes gas demand and according to recent gas forecast studies [6], we can evaluate the natural gas demand values for 2015. This forecast is presented in the third column of table 1 (demand gas units are expressed in million cubic meter – Mm^3).

As referred, these values are aggregated loads for each geographic area. We should not be surprised if we find a higher gas demand in Porto than in Lisbon. The reason is that in Porto geographic node demand, an important electricity generator is included, which raises demand value. Near Lisbon, there is an important electricity generator but its demand is included in the Santarém geographic area.

2.2 Distance Matrix

For the 65 node gas network we must define the distance matrix $[d_{ij}]$, which is an important parameter of the location model. Observing again figure 1, we identify that there are 60 pipelines that interconnect the nodes. For the 65x65 distance matrix values, the 2 x 60 values are filled with the physical pipelines lengths. The others are all the road distances between each pair of nodes. So, except in the principal diagonal line, all the values of the distance matrix are positive.

The parameter value α is the kilometric cost of natural gas transported by physical pipelines, with natural gas in its gas form. The value β, is the same cost for gas transported in virtual pipelines. The β cost is usually greater than α and both values will influence the locating solution of GSUs on natural gas network.

2.3 Fixed Location Costs

Most of gas sources need storage facilities infrastructures and their construction is not suitable or feasible in certain geographic locations. In our model we will consider an explicit cost of locating a GSU at each candidate location node, as seen in the fourth column in table 1.

Because the most appropriate sites to locate the GSUs are seaside points, we consider lower prices for these points than for the interior points.

We can see in table 1 that there are 9 points in the Iberian gas system which have fixed costs of zero. This means that a GSU was already located at these points and such existing gas source facilities cannot be moved. We want to find the location of additional and necessary GSUs, in order to properly supply all the customer loads.

From the nine existing GSUs, seven are marine gas terminals and the other two - La Rioja and Cadiz - are supply injection gas points, respectively from France and Algeria.

Table 1: Nodes data

Nodes	Name	Demand (Mm3)	Fixed Cost (m€)
1	Aveiro	1 071	9 000
2	Beja	242	19 200
3	Braga	1 247	19 200
4	Bragança	223	19 200
5	Castelo Branco	312	19 200
6	Coimbra	662	9 000
7	Évora	260	19 200
8	Faro	593	9 000
9	Guarda	261	19 200
10	Leiria	689	9 000
11	Lisboa	3 205	9 000
12	Portalegre	191	19 200
13	Porto	7 643	9 000
14	Santarém	5 683	19 200
15	Setúbal	1 183	0
16	Viana	375	9 000
17	Vila Real	336	19 200
18	Viseu	593	19 200
19	Corunha	3 442	0
20	Lugo	1 269	9 000
21	Pontevedra	2 909	9 000
22	Orense	1 217	19 200
23	Astúrias	4 074	9 000
24	Cantábria	2 621	9 000
25	Vizcaya	5 447	0
26	Guipuzcoa	4 182	19 200
27	Alava	3 084	19 200
28	Leon	1 724	19 200
29	Palencia	813	19 200
30	Burgos	1 343	19 200
31	Zamora	882	19 200
32	Valladolid	1 777	19 200
33	Soria	585	19 200
34	Segóvia	762	19 200
35	Ávila	472	19 200
36	Salamanca	1 318	19 200
37	Córdoba	3 396	19 200
38	Huelva	2 547	0
39	Sevilha	6 305	19 200
40	Jaén	3 045	19 200
41	Cádiz	4 516	0
42	Málaga	5 286	9 000
43	Granada	3 612	9 000
44	Almeria	1 730	9 000
45	Huesca	1 384	19 200
46	Zaragoza	3 351	19 200
47	Teruel	399	19 200
48	Lérida	3 838	19 200
49	Tarragona	4 701	9 000
50	Barcelona	17 477	0
51	Gerona	4 587	9 000
52	Guadalajara	1 350	19 200
53	Cuenca	1 362	19 200
54	Albacete	1 087	19 200
55	Cidade Real	2 187	19 200
56	Toledo	2 465	19 200
57	Cáceres	1 166	19 200
58	Badajoz	1 897	19 200
59	La Rioja	1 883	0
60	Madrid	21 497	19 200
61	Múrcia	6 871	0
62	Navarra	2 709	19 200
63	Castellon	3 428	9 000
64	Valencia	8 721	0
65	Alicante	6 787	9 000
	TOTAL	192 270	

3 Location Algorithm

3.1 Applied *P*-median Problem

To exemplify the application of lagrangean relaxation to the location p-median problem, we will consider the following binary integer programming problem, with *m* GSUs potencial sites and *n* demand nodes:

$$Z = \text{Min} \sum_{i=1}^{m}\sum_{j=1}^{n} \alpha.d_{ij}.X_{ij} \qquad (1)$$

subject to:

$$\sum_{i=1}^{m} X_{ij}=1 \qquad j = 1,\dots,n \qquad (2)$$

$$\sum_{i=1}^{m} X_{ii}= P \qquad (3)$$

$$X_{ij} \le X_{ii} \qquad i = 1,..,m;\ j = 1,..,n \qquad (4)$$

$$X_{ij} \in \{0,1\} \qquad i = 1,..,m;\ j = 1,..,n \qquad (5)$$

Where:
$\alpha.[d_{ij}]$, is the symmetric cost [distance] matrix, with $d_{ii} = 0,\ \forall i$; α is the kilometric gas transported cost;
$[X_{ij}]$ is the allocation matrix, with $X_{ij} = 1$ if a node i is allocated to node j, and $X_{ij} = 0$, otherwise; $X_{ii} = 1$ if node i has a GSU and $X_{ii} = 0$, otherwise;
P is the number of GSUs (medians) to be located.

The objective function (1) minimises the distance of each pair of nodes in network, weighted by α.
Constraints (2) ensure that each node *j* is allocated to a source node *i*. Constraint (3) determines the exact number of GSUs to be located (*P*). Constraint (4) sets that a demand node *j* is allocated to a node *i*, if there is a UFG at node *i*. Constraint (5) states the integer conditions.
In the Iberian gas system we assume that all demand points are also potential GSUs sites, resulting in the same dimension for indexes, i. e., *m* = *n*.
At this point, we only speak about α transport cost, but if the gas is transported by virtual pipe the β transport cost is implicitly assumed in the algorithm.
To simplify mathematical formulation, the value α is included in distance matrix, obtaining $[D_{ij}]$:

$$Z = \text{Min} \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}.X_{ij} \qquad (6)$$

subject to (2), (3), (4) and (5)

To solve this *p-median* problem (6) applied to Iberian gas system, we propose a lagrangean heuristic, based upon lagrangean relaxation and subgradient optimization.

3.2 Problem Relaxation

We can relax the original problem Z by eliminating constraint (2) and including it in the objective function, weighted by the lagrangean multipliers λ_i. The resulting relax problem is:

$$Z_{Rel} = \text{Min} \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}.X_{ij} - \sum_{i=1}^{n}\lambda_i\left(\sum_{j=1}^{n} X_{ij}-1\right)$$

or, written in a different way:

$$Z_{Rel} = \text{Min} \sum_{i=1}^{n}\sum_{j=1}^{n}\left(D_{ij}-\lambda_i\right).X_{ij} + \sum_{i=1}^{n}\lambda_i \qquad (7)$$

subject to (3), (4) and (5).

The resulting problem Z_{Rel} is the relax or lagrangean problem and λ_i are the parameters of the multiplier lagrangean vector, a non-negative vector.
For a given $\lambda > 0$, problem (7) is solved considering implicitly constraint (3). The problem is solved for different values of *P*, until reaching the right number of GSUs that should be located to minimise costs.
It can be easily demonstrated [7] that $\nu(Z_{Rel}) \le \nu(Z)$. So, we can find that $\nu(Z_{Rel})$ is the inferior bound of the optimal solution to the original problem (6).
The next step is to find the upper bound. It can be founded by solving a lagrangean dual, the problem that maximises the relax problem:

$$W = \text{Max } Z_{Rel}(\lambda) \qquad (8)$$

Due to its nature, problem (8) has some properties that make it difficult to find a dual solution – gap duality. We propose a lagrangean heuristic, combining the subgradient optimization with the feasibility of the solution founded in each iteration. In this case, we obtain a feasible solution which can be improved step by step.
These upper and lower bounds found for the *p-median* objective function will reduce the required computational cost of the original problem Z.

3.3 The Lagrangean Heuristic

The following algorithm is used as the base to the proposed lagrangean heuristic.
Consider the next terminology for the problem:

C – set of nodes already fixed: $C = \{i|X_{ii}=1\}$
UB – upper bound for problem (6)
LB – low bound for problem (6)
X^{λ}- relax problem solution
X_f – relax problem solution after feasibility
ν_f – relax problem value after feasibility
$\nu(Z_{Rel})$ – relax problem value for a given λ

Lagrangean Heuristic

Given $\lambda > 0$;
Set LB = $+\infty$, UB = $+\infty$, C = 0;
Repeat
Solve Z_{Rel}, obtaining X^{λ} and $\nu(Z_{Rel})$;
Obtain a feasible solution, X_f and its value ν_f (**SolutionFeasibility**);
Update LB = max [LB, $\nu(Z_{Rel})$];
Update UB = min [UB, ν_f];
Fix $X_{ii} = 1$ if $\nu(Z_{Rel}| X_{ii} = 0) \geq$ UB, $i \in$ N-C
Update C:
Set $g_j^{\lambda} = 1 - \sum_{i=1}^{n} X_{ij}^{\lambda}$, $j \in N$;
Update the step size θ (**Updateθ**):
Set $\lambda_j = \max \{0, \lambda_j + \theta . g_j^{\lambda}\}$, $j \in N$
Until (**StoppingCriterion**)

The three auxiliary procedures bold outlined in the main algorithm, are briefly described. The **SolutionFeasibility** identifies the median nodes that can be used to produce feasible solutions to original problem Z. As we know x^{λ} is a solution to Z_{Rel} but not necessarily feasible to Z. In this procedure, the median nodes are reallocated to their nearest medians producing x_f. The step sizes used in **Updateθ** procedure are:

$$\theta = \frac{\pi(LS - LI)}{\left\| g^{\lambda} \right\|^2}$$

The control of parameter π is made using the classic control [8]. The **StopCriterion** procedure used is:

a) $\pi \leq 0.005$;

b) LS – LI < 1;

c) $\left\| g^{\lambda} \right\|^2 = 0$;

d) Every GSUs were fixed

We have implemented this heuristic approach to the Iberian gas system, with the data presented in table 1, which is a realist forecast instance of 2015.

The heuristic result will inform us about the right number *P* to locate the GSUs and their optimal location on the network. After these medians are located, it is necessary to allocate the demand points to the gas sources. With the location problem already done, the inherent problem of the allocation will have is computational dimension reduced.

To solve the allocation problem we use the capacitated fixed charge GSU location problem [3], because it was considered that the GSUs production capacity cannot be exceeded. For all the located GSUs, we admit a maximum production capacity of 24 000 mm^3.

3.4 Computational Results

The results of table 2 report the behavior of the implemented location-allocation problem.

Table 2: Location-allocation results

GSU Nº	Location Name	Demand Allocation (nodes)	Transport Mode	Demand Allocation (Mm3)
1	Setúbal	Setúbal		4647,9
		Lisboa	pipe	
		Évora	truck	
2	Corunha	Corunha		8837,5
		Lugo	pipe	
		Pntevedra	pipe	
		Orense	pipe	
3	Vizcaya	Vizcaya		12712,5
		Alava	pipe	
		Guipuzcoa	pipe	
4	La Rioja	La Rioja		16979,9
		Navarra	pipe	
		Zaragoza	pipe	
		Huesca	pipe	
		Lerida	pipe	
		Avila	truck	
		Burgos	pipe	
		Segovia	pipe	
		Soria	pipe	
		Palencia	pipe	
		Valladolid	pipe	
5	Barcelona	Barcelona		24000
		Lérida	pipe	
		Gerona	pipe	
6	Valencia	Valencia		17248,1
		Teruel	truck	
		Castellon	pipe	
		Tarragona	pipe	
7	Murcia	Murcia		14953,4
		Alicante	pipe	
		Albacete	truck	
		Madrid		
8	Huelva	Huelva		9686,4
		Beja	truck	
		Faro	truck	
		Sevilla	pipe	
9	Cadiz	Cadiz		4516,1

10	Madrid	Madrid		24000
		Cuenca	pipe	
		Guadalajara	pipe	
11	Porto	Porto		19285,1
		Braga	pipe	
		Viana	pipe	
		Vila Real	truck	
		Bragança	truck	
		Aveiro	pipe	
		Coimbra	pipe	
		Viseu	pipe	
		Leiria	pipe	
		Santarem	pipe	
		Portoalegre	pipe	
		Castelo Branco	pipe	
		Guarda	pipe	
12	Asturias	Asturias		10619,5
		Cantabria	pipe	
		Leon	pipe	
		Zamora	pipe	
		Salamanca	pipe	
13	Jaen	Jaen		17767,5
		Granada	pipe	
		Cordoba	pipe	
		Badajoz	pipe	
		Caceres	pipe	
		Cidade Real	pipe	
		Toledo	pipe	
14	Malaga	Malaga		7016,5
		Almeria	truck	
			TOTAL	**192.270**

In the first and second column of table 2 we can see the 14 location results obtained from the lagrangean heuristic. The first nine located GSUs are the existing sources in the Iberian gas system, which we have already seen in table 1. As we imposed zero fixed costs, the algorithm found it attractive to install GSUs at these points. The additional 5 GSUs installed complete the optimal location solution for the stated problem.

The third and fourth columns of table 2 are the demand allocation results and the adequate transport mode used for the allocation. As we can see, the demand points within the physical pipeline system are supplied by high pressure network, the others are supplied by gas transport trucks.

The demand points in shadow are self supplied nodes, i. e., they are simultaneously source and demand nodes. To minimize expense each source point should supply its own demand.

We can notice two GSUs that should operate in their maximum capacity production: GSU 5 – Barcelona and GSU 10 – Madrid. In the case of GSU 5, to supply the three allocated demands, the source needs to produce at its maximum capacity but that is not enough to supply node 48´s complete demand - Lerida. This demand point is bi-served, partially by GSU 10 and by GSU 4. In the case of GSU 10 – Madrid, its maximum production is not enough to supply the total allocated demand. However, this is solved by getting some gas from GSU 7.

With this arrangement, the total demand is completely satisfied.

4 Conclusion

The implementation of the Iberian natural gas market is the key to the development of gas industry for Portugal and Spain. Because of the forecasted growth in demand, more GSUs need to be installed to completely supply all customers.

Our work aims at studying the gas source unit location-allocation problem applied to the Iberian natural gas transportation system.

For the location resolution we present a lagrangean heuristic to solve the p-median problem. Because of the heuristic gratifying results, the allocation problem finds its computational size decreased and therefore we can use an exact approach to assign the demand nodes to the proposed GSU located.

The location model proposed shows a good performance in a reduced computational time of two seconds. Apart from that, the developed algorithm is able to capture the richness of the real Iberian network with a proved accuracy of maintaining the existing facilities and installing additional ones.

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