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# MULTI-CRITERIA EVALUATION OF THE EXPANSION OF NATURAL GAS DISTRIBUTION NETWORK BY THE URBAN DYNAMICS

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**Abstract:** The objective of this work is to analyze the expansion of the infrastructure of natural gas distribution, identifying priorities from large metropolis using the energy planning based on urban design tools like urban dynamics and techniques like AHP (analytic hierarchy process). The methodology proposed uses matrices considering the relations between the concept of urban dynamics, quality of life and the possibilities of natural gas displacing other energy forms. The matrices are made up of information about social and urban development, costs of establishing the infrastructure and projections of the consumption potential in various sectors. Relating the consumption to urban development parameters and the real estate future of the areas in study, the methodology allows indicating for each district, the viability of implementing a gas network. As conclusion, the model presents the integration between the cities profile and the natural gas use, by means of a growth natural gas on districts of São Paulo City as a specific case study.

**Keywords:** Energy, natural gas, infrastructure, urban development, analytic hierarchy process



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## INTRODUCTION

Natural gas (NG) is currently the third largest source of primary energy in the world, surpassed only by oil and coal (EIA, 2008).

In the ANP (Brazilian National Agency of Oil, Natural Gas and Biofuels) surveys for the next years, new natural gas fields will be incoming in Brazil. For instance, the Manati field will duplicate de actual gas production in state of Bahia solving in the short-term the problem of natural gas unsatisfied demand. In the Espírito Santo state, the Peroá-Cangoa field emerges as an opportunity of complementing the gas for the Brazilian northeastern and southeastern regions and to reliability the Campos Basin production in the state of Rio de Janeiro. But the Mexilhão field in the São Paulo state, Santos Basin, as a prelude of the context of the pre-salt reservoirs, will be anticipating the gas production as definition of the federal Brazilian administration (BNDES, 2006). Also in January of 2008, in the pre-salt hydrocarbons offshore Brazilian reservoirs of Santos Basin (state of São Paulo) another well was discovered. The reserve that was entitled Jupiter is a large natural deposit for natural gas and light-oil, in deep waters estimated in very large gas mega-field that, despite demanding large investments, will make Brazil double its reserves (GASBRASIL, 2008). With this favorable forecast of natural gas supply and considering its various uses, this work focuses on market gas demand in sectors like residential, commercial, services and industrial.

In this work, an analytical methodology that integrates the understanding of the urban dynamics to the strategies of expansion in the natural gas distribution network is considered, characterizing gas consumption possibilities and attractiveness for the districts, composing a city.

The methodology is developed by gathering information such as family income, demographic density and construction area, percentage of land use, number of households as well as commercial, service and industrial establishments, number of real estate as well as indicative information released by the Urban Plan of the city regarding the increments in the peripheral districts. By relating the gas consumption estimated by each type of land occupation and the cost for expanding the gas distribution network, the model will indicate, for each neighborhood, the viability of implementing a gas network as well as the places with potential for growing density in the existing gas distribution system. In this paper, examples of essential information that compose the methodology are presented for six districts of São Paulo city (Brazil): Ipiranga,Tatuapé, Penha, Vila Matilde, Socorro and Vila Formosa, which have different socioeconomic and geographical profiles. Finally, the model tested for São Paulo will be generalized in a computer model, which allows its use in other Brazilian cities, pointing out the possibilities of natural gas as a final option of energy in the urban uses, besides presenting guidelines for the Urban Plans and the sustainable gas infrastructure incorporation in the cities (Udaeta *et al.*, 2004).

## METHODOLOGY

The methodology based on urban indicators (Massara, 2007) has the main objective of developing procedures that allow to analyze and to guide the expansion and the growing density of the natural gas network inside a municipal district through the study of the development among several parameters and also to analyze the urban dynamics that determines the expansion of the metropolitan natural gas infrastructure (Williams, 1962; Forrester, 1969). The systemic model was elaborated according to the following stages:

- Identification, characterization and organization of the main interventionary factors;
- Definition of the study cells (streets, districts, suburbs) according to the availability of information about the parameters;
- Hierarchization of quantitative and qualitative parameters through the attribution scale of priorities that unifies the parameters units, so that they can mathematically be treated;
- Evaluation of the system with the purpose of directing the choice based in theoretical guidelines and also in the application of the Analytic Hierarchy Process (AHP) supporting the computer model (Saaty & Vargas, 1982);
- Validation of the decision-making process for the planning of the expansion of natural gas distribution infrastructure through case study in the city of São Paulo and comparison with the results obtained through the model and the mapping of the existent implanted net.
- Validation through comparison with the Analytic Hierarchy Process (Saaty, 2006).

In this preliminary analysis, all the parameters have been used with influence distribution indices in intervals from 1 to 5. The attribution of this scale is related to the use of the cardinal and semantic scales (Allen, 1987). At the end of the study, it will be possible to determine whether this linear scale is valid or not, via test and comparison with analysis of multiple-criteria models that also use the priority scale as a tool in the decision-making process (Saaty, 1980). Similarly, the algorithm used in this paper for the determination of the attractiveness index must be revised and compared with the results obtained according to the AHP methods.

The chosen hierarchization is the same used by the *AHP* (Saaty, 1980; 2006), which allows the verification between algorithms of this method and that one of the proposal modeling (in this work), according to the association presented in **Table 1**.

## The proposed model and the information systems

The sets of data are composed of four systems referring to the study area, according to the Brazilian official denomination "SEMPLA" (São Paulo, 2002). These systems establish an attractiveness index for natural gas infrastructure expansion with regards to the urban development of the cities.

## First System: Life Quality Indicators (LQ)

This system is represented by three factors, all of which represent numerical values that are distributed in the five groups that have been initially described.

*Social Exclusion Index (SEI)*: it has the objective of identifying the social development degree of the districts (Sposati, 2000) considering the existence of social equipments (green areas, bus lines, number of schools and hospitals). The final index attributed to each one of the districts lies within the interval that ranges between -1.00 (reflecting the worst exclusion situation, i.e., the first group) and +1.00 (reflecting the best inclusion situation, i.e., the fifth group).

*Human Development Index (HDI)*: This is an adaptation of the index created by the United Nations Organization (UNO), with the objective of comparing the degree of human development according to the districts. It comprises factors such as education and basic conditions of health in each district (IBGE, 2008). These indicators are transformed in intervals that range between 0 (first group, the worst development condition) and 1 (fifth group, referring to the best conditions).

*Priority Infrastructure (WS, SS, SI)*: water supply, sewer system and streets illumination are considered "priority infrastructures" (São Paulo, 2002). This parameter corresponds to the idea that a given district will not be attractive to natural gas network if it still does not possess such infrastructure. The index considers the mean percentage of the actual conditions of the three nets, expressed in five groups in intervals of 20%.

**Table 1.** Adaptation of AHP scale to natural gas study

| Group | Semantic scale for natural gas | AHP scale |
|---|---|---|
| 1 | Low attractivity to network installation | 1 |
| 2 | Low to medium attractivity to the installation of the network | 3 |
| 3 | Medium attractivity to the installation of the network | 5 |
| 4 | Medium to high attractivity to the installation of the network | 7 |
| 5 | High attractivity to the installation of the network | 9 |

Source: Massara (2007) based on Saaty (2006).

## Second System: Urban Plan Indicators (UP)

These indicators combine qualitative parameters (land use, urban development and zoning) and quantitative (urbanization rate and real estate). For the analysis of non-numerical values, the systems are based on the mapping and classification of the Urban Plan of São Paulo city and its adaptation for any city, in order to verify the types of land occupation (residential, commercial, industrial and services) and their expansion perspectives. This is carried out with the purpose of effecting the elaboration of a neighborhood profile with larger tendency to industrial developments (higher attractiveness for natural gas), and follows the natural gas consumption projection listed below.

*Land Use* (*Lures, LUcom, LUserv, LUind*): considering the largest percentage of streets with certain use type, this concept is based in the occupation characteristic of the city districts represented in the urban plan map (São Paulo, 2006). Although the municipality considers several occupation categories in view of the natural gas attractiveness, groups have been classified according to five main uses:

1st. Group: horizontal residential occupation;
2nd. Group: mixed use (commercial and residential horizontal);
3rd. Group: vertical residential occupation;
4th. Group: mixed use (commercial, services and residential vertical);
5th. Group: mixed use (residential and industrial).

*Urban Development* (*UD*): the basis of this concept is the Urban Plan of São Paulo city (São Paulo, 2002; 2006), corresponding to five "macroareas" that comprehend the present specifications and the future urban developments, as represented in the following five groups:

1st. Group: environmental protection – limits of public areas and preservation areas;

2nd. Group: urbanization and urban qualification – areas predominantly occupied by low income families with high concentration of irregular constructions;
3rd. Group: requalification – areas with good infrastructure although presenting many empty properties;
4th. Group: urbanization in consolidation – areas in condition to attract real estate investments in residences, services and commercial establishments;
5th. Group: consolidated urbanization – areas formed by consolidated neighborhoods inhabited by population of medium and high income and good urbanization conditions.

*Land Use Rule (Zoning - Z)*: This refers to the rule imposed by the Municipality (São Paulo, 2002; 2006) that limits land use and the destination of the several sections of the city for determined uses (trade, services, housing, industries). The natural gas attractiveness predominance is, in this case, represented by the following five groups:

1st. Group: residential zone of low density / zone of environmental protection;

2nd. Group: residential zone of medium density / mixed zone of low density;

3rd. Group: residential zone of high density / mixed zone of medium density / special uses;

4th. Group: mixed zone of high density;

5th. Group: great industrial zone occupation.

The definition of "mixed zone" corresponds to the combination of the residential use, services and commercial uses.

*Urbanization Rate (UR)*: corresponds to the percentage of the total district area occupied by urban use (blended residences with commerce, services and industries) as compared to the total population (São Paulo, 2006; IBGE, 2008), which is represented in intervals of 20%.

*Real Estate for residential and service market (REres, REserv)*: this concept is related to the Construction Code about building facilities for natural gas in new constructions (International Code Council, 2000), which must increase the consumption of natural gas. In order to attribute the attractiveness index, five groups have been selected which were based on the largest and the smallest number of district releases as reported in a survey by EMBRAESP (2008).

**Third System: Potential of Natural Gas Consumption Indicators (PNGC)**

In this data system, the characteristics of the neighborhoods in terms of street extensions are stored. All parameters are numerical values, thus simplifying the creation of the five groups using the numerical simple division of values that are obtained by the Brazilian institutions IBGE (2008) and São Paulo (2002; 2006), as follows.

*Demographic Density (DD)*: corresponds to the ratio between the number of resident people and the total area of the district (SEADE, 2008), considering that "larger people concentrations generate larger energy demand".

*Family Income (FI)*: corresponds to the minimum wages in the homes of the district (IBGE, 2008; SEADE, 2008), considering the relationship between "income and energy consumption possibilities".

*Stratification according to the type of land use, households and economic activities (Sres, Scom, Sserv, Sind)*: the basis of this method considers that both the demand for natural gas and the attractiveness of the district receiving the canalized gas system increase with the number of domiciles or establishments with economic activities in a specific district (Groenendaal, 1998). The division in establishments is made through the Economic Activities Cadaster (IBGE, 2003) and for the households through the "Census" (IBGE, 2008; SEADE, 2008). Those data enter in the file as "number of units" and the system automatically transforms them in influence indices from 1 to 9, according to the lowest and the highest numbers obtained for each district. Besides the internal scale, the program allows the insertion by the user of one external influence that is multiplied by the attributed value. This comes already as a function of the number of units that distinguish the activities that are more appropriate to the use of natural gas or, for other reasons, are more attractive to the natural gas concessionaire.

In the following example, the external influence has not been attributed. All parameters have only the internal scale from 1 to 9.

**Fourth System: Civil Construction Indicators (CC)**

The function of this system is to represent values associated with the cost of the underground infrastructure implementation. As for other numerical parameters, the five groups have been elaborated by simple division of the acquired values expressed by the four factors below.

*Natural Gas Infrastructure Extension (E)*: corresponds to the distance between areas that can be served and others that are effectively attended by natural gas. The rule for the influence attribution is “the smaller the distance, the larger the influence attributed for natural gas attractiveness”.

*Natural Gas Distribution Ramification (D)*: corresponds to the total sum of the internal streets that may be attended by natural gas supply systems. The parameters are also considered in the rule: “the smaller the distance, the larger the influence”. Thus, districts partially located in served areas are attributed “five” as the influence index, expressing the best attractiveness conditions.
*Built Density (BDres, BDcom, BDserv, BDind)*: this factor is obtained by the ratio between the built area according to the type of land use (residential, commercial, services and industrial) and the total area of the district (São Paulo, 2006). In districts with high industrial density, lower investments with ramifications are considered (“capillarity” of the distribution network).

*Avenues and Streets of Great Importance Traffic (T)*: even with the constructive process evolution, the parameter indicates the importance of the district as a connection among neighborhoods and other municipal districts and the special attention that must be given to the interdiction plan. The number of avenues (or streets) is obtained by simple consultation of any streets guide and by counting avenues and streets of larger extension within any given district.

According to the description in the methodology, all the values gathered are unified to the same unit (percentage) and divided in five zones of attractiveness that are converted in the hierarchisation scale of 1 to 9. After the weights are attributed, they are submitted to the calculation of “Attractiveness index”, whose algorithm is based on the simple sum of the weights for each area of study as summarized in **Table 2**.

**Table 2.** Summary of the algorithm for the Attractiveness Index.

| **Attractivity Index by Information Systems** |
| --- |
| LQ= (ISE+HDI+WS+SS+SI)/n |
| UP= LUres+LUcom+LUserv+LUind+UD+Z+UR+REres+REserv)/n |
| PNGC= (DD+FI+Sres+Scom+Sserv+Sind)/n |
| CC= (E+D+BDres+BDcom+BDserv+BDind+T)/n |
| **General Attractivity Index** |
| IG= (LQ+UP+PNGC+CC)/n |

Source: Massara (2007). Note: *n* represents the number of parameters effectively used. The acronyms are described in methodology.

## RESULTS AND DISCUSSION

As suggested in the recommendations about natural gas policy (Meier, 1997; IESP, 2004), the choice of São Paulo (capital of São Paulo State) as an all-gas city, is to demonstrate the complete utilization of natural gas in all its applications. In the context of this work, the choice has background in:

- The possibility of increasing the density of use of the current grids: the increment of the factor of utilization of the infrastructure implanted in the expanded center, besides the extending the consumption market can leverage the financing of the network expansion.
- The process of civil construction has evolved with the use of a no-dig method of cutting trenches, the *trenchless technology* (Istt, 2008; Najafi, 2005). It reduces the trouble caused by the interdiction of traffic ways to rebuild the pavement, thus making its execution cheaper, mainly in already consolidated urban areas.
- As mentioned by Moutinho dos Santos *et al.* (2002, p. 162): “In the São Paulo municipality, along the roads at the margins of Tietê and Pinheiros rivers, the greatest commercial areas in the country are concentrated here, with various shopping centers and large office buildings. All of them are located less than 2 km from the high pressure Comgás (gas utility) pipe-ring, but rarely it is used”.

This situation will be the same in the next years, according to the map (Comgás, 2007). The map of the gas utility shows the natural gas grid distribution in the city of São Paulo, in other words, which district is already served by the network, permitting the selection of areas not served for testing the model proposed in this work.

**Figure 1** shows the city of São Paulo within the metropolitan region of São Paulo.

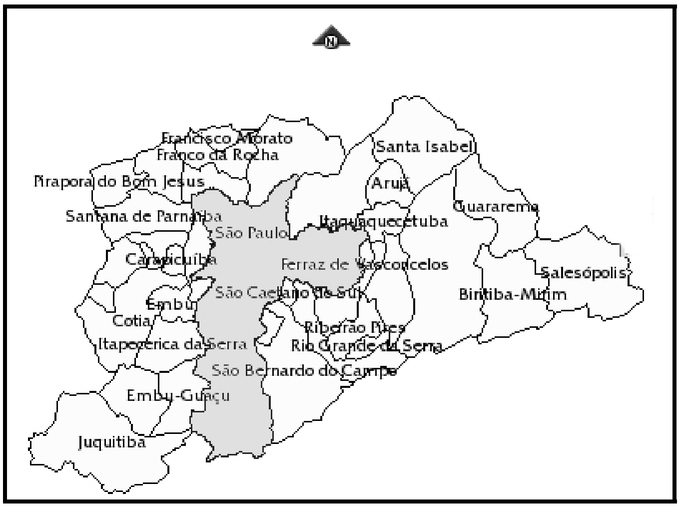


**Fig. 1.** City of São Paulo (ash area) inserted in the Metropolitan Region. Source: SEADE (2008).

Since the case study has been used in the city of São Paulo, it has been divided in 96 districts in conformity with the information reported by the local Urban Plan Department (São Paulo, 2002; Massara, 2002).

**Figure 2** introduces the positioning of the districts selected in this paper, emphasizing the different geographical and social characteristics of each one.

The selected districts represent areas of the city with great urban transformations. Some of them face a process of intensification of the residential real estate market (Ipiranga, Tatuapé and Penha), attracting investments in several economic activities in order to respond to that new occupation style. Others have low family income but possess industrial areas that must consume natural gas (Vila Formosa and Socorro).

Others present great urban complexity, functioning as a "bedroom cities", with land use predominantly composed by habitational groups (Vila Matilde).

In order to demonstrate the use of the model developed in this work, for instance, one application is presented across the **Table 3**.

Therefore, in this example, the following simplifications were considered:

- Calculation of the attractiveness index, using the "General" grouping (without the division in information systems) and its respective ranking;
- Study area: districts;
- Extra weight to emphasize the segments for the natural gas use = 1.0 for all the activities.
- Algorithm application according to the **Table 2**.


**Fig 2**. The 6 selected districts in São Paulo municipality (capital city). (Note: unscaled figure).
Source: SEADE (2008).

**Table 3.** Attribution of weights according to the four information systems

| Parameters | Selected Districts of São Paulo City | | | | | |
|---|---|---|---|---|---|---|
| | **Ipiranga** | **Tatuapé** | **Penha** | **Vila Matilde** | **Socorro** | **Vila Formosa** |
| ISE | 7 | 9 | 7 | 7 | 9 | 9 |
| HDI | 3 | 5 | 5 | 5 | 7 | 7 |
| WS | 9 | 9 | 7 | 9 | 9 | 9 |
| SS | 9 | 9 | 9 | 9 | 1 | 9 |
| SI | 9 | 9 | 9 | 5 | 9 | 7 |
| LU res | 3 | 5 | 5 | 7 | 3 | 9 |
| LU com | 5 | 7 | 7 | 5 | 3 | 3 |
| LU serv | 3 | 9 | 9 | 5 | 1 | 1 |
| LU ind | 5 | 1 | 1 | 1 | 7 | 1 |
| Z | 9 | 7 | 7 | 5 | 5 | 7 |
| UD | 9 | 5 | 5 | 5 | 9 | 9 |
| UR | 9 | 9 | 9 | 9 | 9 | 9 |
| RE res | 5 | 9 | 5 | 1 | 1 | 3 |
| RE serv | 3 | 9 | 9 | 1 | 5 | 1 |
| DD | 3 | 3 | 5 | 5 | 1 | 5 |
| FI | 3 | 5 | 1 | 1 | 3 | 3 |
| S res | 5 | 3 | 5 | 3 | 1 | 3 |
| S com | 9 | 7 | 9 | 3 | 9 | 5 |
| S serv | 5 | 7 | 9 | 5 | 5 | 5 |
| S ind | 9 | 5 | 5 | 1 | 9 | 3 |
| D | 9 | 9 | 3 | 5 | 9 | 3 |
| E | 5 | 7 | 1 | 5 | 9 | 5 |
| T | 1 | 1 | 1 | 3 | 1 | 3 |
| BD res | 5 | 9 | 7 | 7 | 3 | 9 |
| BC com | 9 | 3 | 7 | 5 | 3 | 9 |
| BC serv | 9 | 3 | 7 | 5 | 3 | 9 |
| BC ind | 1 | 5 | 3 | 1 | 9 | 1 |

Source : Massara (2007) based on Seade (2008), São Paulo (2006).

**Table 4.** Results for the case-study – The general attractiveness index and its respective ranking

| District | General index | AHP index (%) | General Ranking | AHP ranking |
|---|---|---|---|---|
| Ipiranga | 6,1 | 18,9% | 2º | 2º |
| Tatuapé | 6,3 | 22,2% | 1º | 1º |
| Penha | 5,9 | 16,8% | 3º | 3º |
| Vila Matilde | 4,7 | 10% | 6º | 6º |
| Socorro | 5,4 | 15,6% | 5º | 5º |
| Vila Formosa | 5,6 | 16,5% | 4º | 4º |

Source: Massara (2007) based on Saaty (2006).

**Table 4** resumes the attractiveness ranking for five municipal districts for the natural gas expansion projection. From the results listed therein, one may conclude that the districts with better positions contemplate mixed land use (Tatuapé is the best example of which) and equality of consumption projection in all uses, associated to a larger demographic density and larger family income.

The first units in the ranking of the model are districts with the largest development in the real-estate market, largest leeway of zoning. These districts are nearest to the areas already served and, of course, have the largest forecast of natural gas consumption, mainly, in the vertical residential use (with highlight for the following districts: Ipiranga, Tatuapé and Penha).

The rest of the districts concentrate the least income, horizontal residential use and a small commercial, services and industrial concentration (Vila Formosa and Socorro). Apart from the characteristics of the intermediate group, the last classification (Vila Matilde) is in an area with environmental limitations to expansion and, therefore, of small urban development.

The comparison between the ranking using AHP (Saaty, 2006) and the model ranking (Massara, 2007) has satisfactory results (presented in **Table 4**).

The model based on urban indicators has presented coherent results when tested in the city of São Paulo. It has been demonstrated that the model proved to be a good calculation tool with a reasonable precision degree, being easily understood and functioning as an auxiliary in the decision-making process for the natural gas expansion infrastructure in the Brazilian cities.

However, in order to have greater potential of expansion of the natural gas grid service, it is necessary that there exists strengthening of the relation between the utilities, network engineers of natural gas pipeline facilities and all the civil construction related to the urban plans. In this case, it is good looking for the development of equipment for the diverse purposes that can utilize natural gas, including the formal assisting from the public entities in the implementation of infrastructure and in advertising of natural gas use as an agent for urban development as well.

Thus, the creation of a residential and commercial market is based on the current use of PLG (petroleum liquefied gas) and on the gradual introduction of natural gas in daily activities, thus inducing customers to the use of natural gas and enabling the development of natural gas canalization and distribution.

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