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Optimal design of a gas transmission network: A case study of the Turkish natural gas pipeline network system

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Optimal design of a gas transmission network:

A case study of the Turkish natural gas pipeline network system

by

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{To my family…}

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ABSTRACT

Turkey is located between Europe, which has increasing demand for natural gas and the geographies of Middle East, Asia and Russia, which have rich and strong natural gas supply. Because of the geographical location, Turkey has strategic importance according to energy sources. To supply this demand, a pipeline network configuration with the optimal and efficient lengths, pressures, diameters and number of compressor stations is extremely needed. Because, Turkey has a currently working and constructed network topology, obtaining an optimal configuration of the pipelines, including an optimal number of compressor stations with optimal locations, is the focus of this study. Identifying a network design with lowest costs is important because of the high maintenance and set-up costs. The quantity of compressor stations, the pipeline segments` lengths, the diameter sizes and pressures at compressor stations, are considered to be decision variables in this study. Two existing optimization models were selected and applied to the case study of Turkey. Because of the fixed cost of investment, both models are formulated as mixed integer nonlinear programs, which require branch and bound combined with the nonlinear programming solution methods. The differences between these two models are related to some factors that can affect the network system of natural gas such as wall thickness, material balance compressor isentropic head and amount of gas to be delivered. The results obtained by these two techniques are compared with each other and with the current system. Major differences between results are costs, pressures and flow rates. These solution techniques are able to find a solution with minimum cost for each model both of which are less than the current cost of the system while satisfying all the constraints on diameter, length, flow rate and pressure. These results give the big picture of an ideal configuration for the future state network for the country of Turkey.

CHAPTER 1

INTRODUCTION

1.1. Motivation

Natural gas has powerful importance according to its economic and environmental benefits. It is one of a major source of electricity among energy sources of coal, nuclear and petroleum. The importance of natural gas is that when it burns, it releases cleaner energy than dirty coal and other polluting energy resources. Also, if natural gas is used widely in the world, pollution that causes global warming during the combustion will be less and our world will be much more livable. Positive environmental effects and several possible applications of natural gas will make this energy source increasingly important to meet demand of energy in many countries in the world.

Since 1995, the consumption and production of natural gas throughout world has been steadily growing from nearly 1600 billion cubic meters to closely 3200 billion cubic meters in 2011 as we can see from Fig. 1, which is given as information by the Statistical Review of BP about World Energy (June 2011).

Moreover, it is estimated that natural gas consumption rate will continue to grow geometrically to nearly 4.33 trillion cubic meters in 2035, with an average growth rate of about 1.6% per year (International Energy Outlook 2011, EIA). Production of natural gas increased by 7.3% in 2011 in the world, the largest increase since 1984 (EIA). Growth of natural gas production stayed above average in all locations while the record of Russia was the largest production increment. With production of natural gas, consumption rate also increased by 7.4%, which is also higher than the average growth in all parts of the world, except the Middle East (EIA).
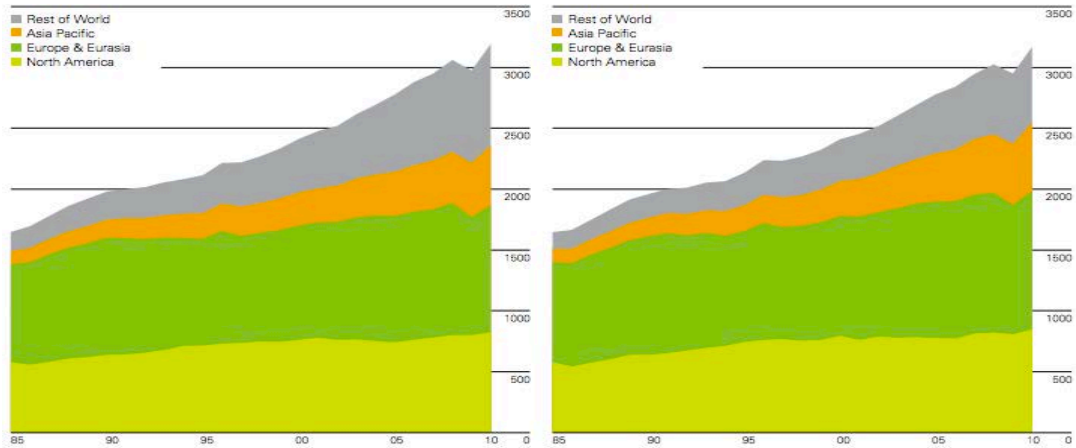
Figure 1. Natural gas production/consumption by region in billion cubic meters (Statistical Review of World Energy by BP, 2011)

An important part of energy demand is being supplied by natural gas, coal and oil currently. By considering this factor, International Energy Agency (IEA) projected that these resources will be used to supply the demand within a period from 2009 to 2035.

Table 1. World`s primary energy consumption on energy resources basis and consumption projection (million tons of equivalent oil - Mtep)
(Source: IEA WEO 2010 New Policies Scenario)

	2009	2015	2020	2030	2035	2009-2035* (%)
Coal	3.294	3.944	4.083	4.099	4.101	0,8
Oil	3.987	4.322	4.384	4.546	4.645	0,6
Natural Gas	2.539	2.945	3.214	3.698	3.928	1,7
Nuclear	703	796	929	1.128	1.212	2,1
Hydropower	280	334	377	450	475	2,1
Biogas and Garbage	1.230	1.375	1.495	1.761	1.911	1,7
Other	99	197	287	524	690	7,8
Total	12.132	13.913	14.769	16.206	16.961	1,3

*Annual average rate of increase

Use of energy is becoming more important according to environmental reasons.

Because of environmental reasons and usage ease of natural gas demand will be increasing position in future until 2035 according to estimation of EMRA, 2011. The primary consumption of the world for energy resources and the projection of consumption within the period of 2009-2035 are shown in Table 1.
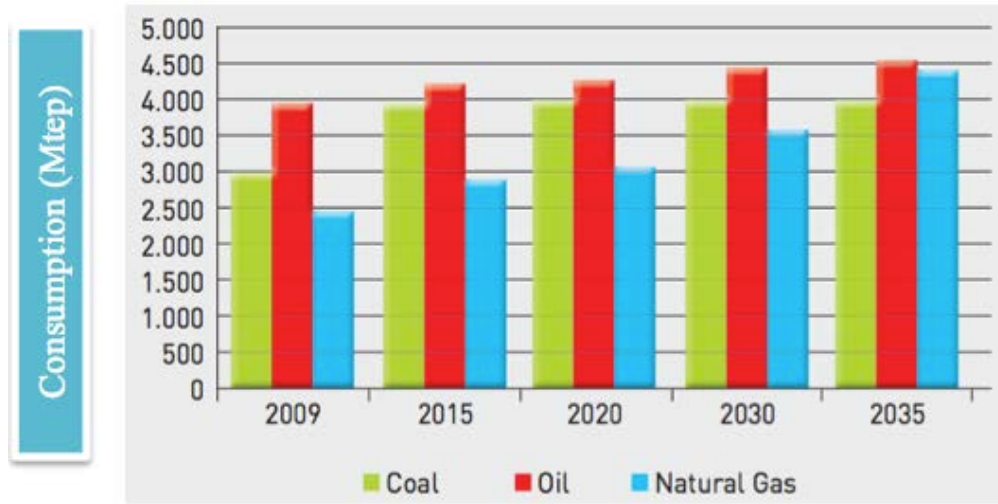
Figure 2. World`s primary energy consumption and consumption projection (million tons of equivalent oil - Mtep) (Source: Energy Market Regulatory Authority (EMRA))

As we can see from table 2, the USA, China, India, Russia and Japan are taking the front places according to consumption of energy in the world, while Turkey is taking 19th place in same table.

A review of the consumption of primary-energy by sectors points out that the sector of electricity generation has the fastest increase (EIA). It is estimated that the consumption of energy will be around 57% until 2030 for electric generation (EIA, 2011). Although a decrease in the usage of energy for transportation has been seen in OECD countries, industrial usage of energy follows a stationary progress, while in non-OECD countries and in rapidly developing countries; the industry sector induces an increase of the energy consumption (EIA).

Table 2. Primary energy consumption figures and shares by countries (BP Statistical Review of World Energy 2011)

	Consumption as end of 2009 (Mtep)	Consumption as end of 2010 (Mtep)	Change from 2009 (%)	Share in Total Consumption (%)
USA	2.204,1	2.285,7	3,7	19,0
Canada	312,5	316,7	1,3	2,6
Brazil	234,1	253,9	8,5	2,1
France	244,0	252,4	3,4	2,1
Germany	307,4	319,5	3,9	2,7
Italy	168,3	172,0	2,3	1,4
Spain	146,1	149,7	2,5	1,2
Russia	654,7	690,9	5,5	5,8
Turkey	101,0	110,9	9,8	0,9
Iran	205,9	212,5	3,2	1,8
S. Africa	118,8	120,9	1,7	1,0
S. Arabia	187,8	201,0	7,0	1,7
India	480,0	524,2	9,2	4,4
Indonesia	132,2	140,2	5,9	1,2
Japan	473,0	500,9	5,9	4,2
South Korea	236,7	255,0	7,7	2,1
Australia	125,6	118,2	-5,8	1,0
China	2.187,7	2.432,2	11,2	20,3
UK	203,6	209,1	2,7	1,7
World Total	11.363,2	12.002,4	5,6	100,0

Table 3. Energy consumption forecast in Turkey according to energy resources (%) (Source: Salvarli, 2006)

Resource/Years	1990	1995	2000	2010	2020
Coal	31.1	27.2	26.6	30.6	39.5
Petroleum	45.6	46.5	42	28.9	24.3
Natural Gas	5.9	10.1	18.8	27.2	22.8
Nuclear	---	---	---	2.9	5.8
Water	3.7	4.8	4.1	4.2	2.8
Other	13.7	11.4	8.5	6.2	4.8

Table 3 shows the energy consumption in Turkey data before and forecast after 2010. According to this projection, natural gas consumption`s share will be 22.8% in 2020. This proportion will be very close to consumption of coal and petroleum in future.

1.2. Natural Gas Usage by Sectors

The long-term demand for natural gas is affected by several factors according to the supply and logistic chain parts, which start from production and transmission systems and end with distribution, marketing and customers (naturalgas.org). To examine natural gas demand most beneficially and effectively, we need to consider demands with its sectors that are using energy resources especially using natural gas as energy sources. The three most important sectors are: demand of residential & commercial, industrial and electric generation demand.

Residential & commercial: Residential energy demand is expected to increase 4-5.5% between 2009 and 2035 according to the Energy Information Administration (EIA). The residential sector is responsible for 18% of all consumption in the world (EIA)(see figure 5).

It is believed that residential heating applications probably will be the most crucial and effective future driver for natural gas demand in the residential sector. Thus research focuses on the design of a natural gas network especially for meeting Turkey`s demand of natural gas, mostly for heating applications and industrial usage more efficiently and effectively. In Turkey, approximately 78% of natural gas consumption is made by the residential and industrial applications (see figure 3) (EMRA, 2011).
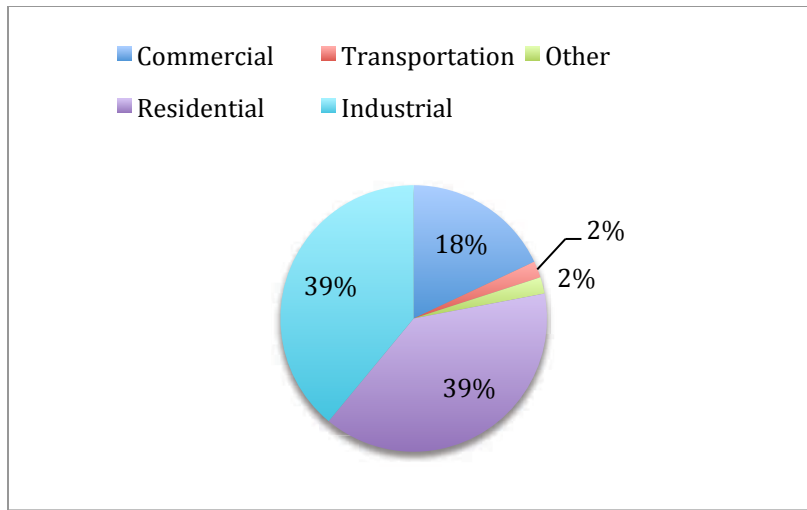
Figure 3. Natural gas consumption by end use in Turkey in 2011 (Source: Bloomberg)

Industrial: As residential and commercial sector, industrial sector`s energy demand is also expected to increase at an average rate of 1.1% through 2035 by EIA.

The commercial sector consumes 12% of its energy from natural gas and will continue to do so through 2035. The EIA points out that industrial energy demand will increase at a rate of 0.9% per year until 2035. Industrial demand is responsible for 30% amount of natural gas demand (EIA) (see figure 5).

Industrial usage of natural gas is also motivation for this case study of Turkey to meet the energy demand and to increase the efficiency of industry.

Electric generation: It is estimated by EIA that the demand of electricity will be increasing by an average rate of 1% per year until 2035.

Natural gas-fired electric generation measured 25% of all generation in 2011 while it is predicted to be 30% of all generation in 2040 by EIA (see figure 4). The increasing demand for electricity combined with the predicted increase in the proportion of generation from natural gas shown in figure 4 imply that the demand for natural gas from the energy sector will be higher in future that it is today.
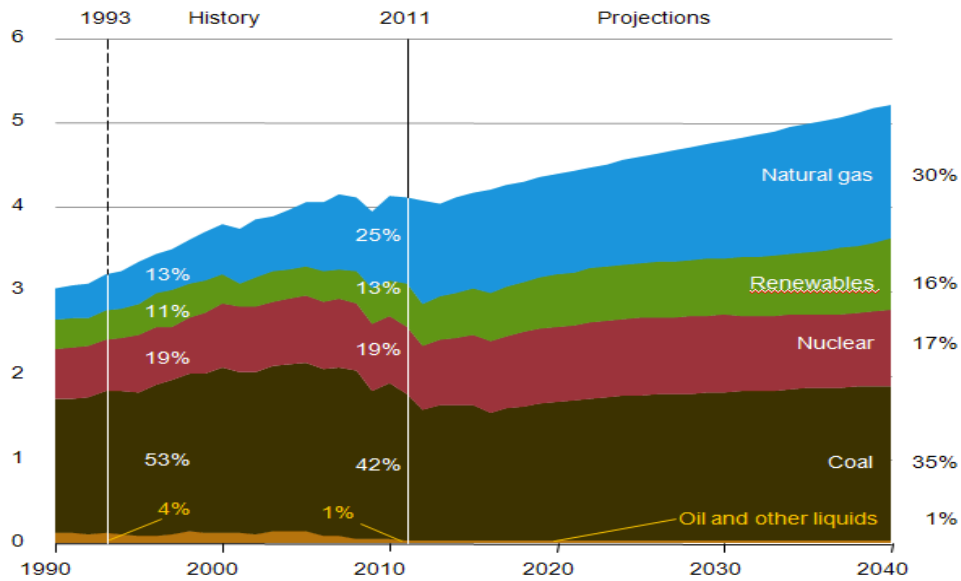
Figure 4. Generation of electricity by fuel (trillion kilowatt-hours per year) (Source: EIA)
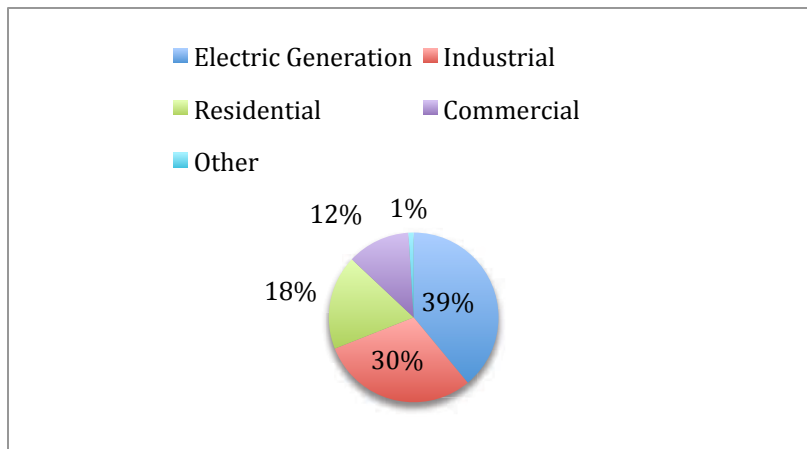
Figure 5. Natural gas consumption by end use in the world in 2012 (Source: EIA)

To summarize; the residential use of natural gas usage is measured at18%, the commercial usage accounts for 12%, usage by industry is measured at 30%, the electric power production is responsible for 39% and the other usages are measured at 1% in the world in 2012 by AER as shown in Figure 5 (AER, 2012).

The largest sector for consumption seems to be industrial sector for natural gas through 2035 whose expected proportion is 40% (International Energy Outlook 2011). The second largest consumption for natural gas is made by the electric power generation in 2012. Namely, natural gas is still protecting its importance for industrial and electricity sectors` source of energy.

The process of getting the natural gas out of the ground consists of seven stages, which are exploration, extraction, production, transportation, storage, distribution and marketing. Also, these stages are a part of supply chain and logistic processes. The well-known website (http://naturalgas.org) about natural gas defines these stages briefly as following:

Exploration; is how natural gas is found and how companies decide where to drill wells for it.

Extraction; is about the drilling process and it searches the answer of how natural gas is took out from its underground reservoirs to the surface.

Production; is a process of bringing out the natural gas from the underground.

Transport; is transportation of natural gas from the processing plant to local distribution companies across a pipeline network.

Storage; is responsible for the storage of natural gas.

Distribution; is a stage of delivering natural gas from the major pipelines to the end users.

Marketing; includes the buying/selling activity from the natural gas marketers.

1.3. Problem Statement

Considering an energy company (Botas, Turkish Petroleum Pipeline Corporation), which is one of the two biggest companies in the energy sector, strategically crucial for Turkey and focusing on especially natural gas; the most important factor is minimizing cost of operation, cost of maintenance, cost of pipeline and cost of compressor or maximizing profit with current business aspect. Also, considering these cost related factors, the best way to increase profit or decrease cost is

to find the relevant problem and solution methods, then to apply these solution techniques to solve the problem that affects the system more than other factors. As the Turkish natural gas pipeline network system has already been designed and its topology chosen, we choose to optimize the remaining aspects of design of the Turkish gas transmission network.

In a natural gas pipeline system, there are several factors existing to succeed in delivering natural gas to end-users. These factors are the diameter of the pipeline segments, lengths of the pipelines, suction and discharge pressures, flow rates, and number of compressor stations. If we change any of these factors, we will get different costs and profits according to current design of network. Considering our case problem, its challenges and issues, we decided to apply suitable models that were created by Edgar et al. (1978) and Tabkhi et al. (2009) to the Turkish natural gas pipeline network system. The advantage of these models is that they can only be applied to gas pipeline systems like Turkish natural gas network system, which are already designed. After considering this case problem about Turkey and these cost related issues, we will seek the optimal values of the main decision variables which are compressor station quantity, length of pipes, diameter sizes, pressures, flow rates, and the resulting cost for our current natural gas pipeline network system.

The minimum total cost of operation per year including capital, operating and maintenance costs are targeted to be the criterion for the optimal configuration of the natural gas pipeline network for Turkey.

1.4. Literature Review

There are many types of optimization techniques and models related to natural gas systems especially related to natural pipeline network systems in literature. These optimization models and techniques can be applied separately in production and transportation of natural gas and also in the natural gas market.

Babu et al. (2005) presented a model similar to the optimization model of our study to design the optimal gas transmission network. However, the difference between our model and their model is that they used the differential evolution (DE) (evolutionary computation technique) that is also able to find the optimal diameter measure, lengths, pressures and number of compressors. To solve the real-valued function, differential evolution method can be one of the best genetic algorithms.

Adeyanju and Oyekunle presented an optimization procedure of natural gas transmission network by using the Reduced Gradient algorithm, which is a mathematical optimization technique, like we used in our case of Turkey. By guiding this optimization technique, they determine the optimum economical conditions for transporting natural gas with pipelines and compressor stations. Finally, they applied the same model to Excravos Lagos pipeline network system. Their model is very similar to our model and they got the main idea from our first source model, which is constructed by Edgar et al. (1978).

Other excellent references on network modeling and network optimization of gas transmission solution algorithms including Rothfarb et al., (1970), Edgar et al. (2001), Edgar et al. (1978), and Babu et al. (2008).

De Wolf and Smeers (2000) proposed a linear programming model to get the optimal dimensioning of natural gas pipelines as the least gas purchase problem. This problem has the nonlinear constraints with the linear approximation. The authors used the simplex algorithm to solve the problem. According to the authors and their model, the performance of the model highly depends on the initial points.

To the best of our knowledge and literature review, so far, a very few studies have been done and applied on Turkish natural gas market and its pipeline network design. Although the limitations of the literature studies about Turkish natural gas pipeline system, except some IEA and OECD studies, is a considerable challenge for us, the best, effective and beneficial solution techniques is combined for applying them to current

Turkish natural gas network system.

In this thesis, we will consider the application to the gas transmission network problem of the global optimization techniques. One of these techniques has been well established by Edgar et al. (1978) and Edgar et al. (2001), and the other one is created by Tabkhi et al. (2009).

1.5. Thesis organization

In this study and thesis, our goal is providing a big picture of the Turkish natural gas system and is pointing out to problems for designing of pipeline networks of the natural gas.

This thesis is organized and presented through eight chapters. Chapter 1, Introduction, describes the motivation behind this work along with the objectives and organization. It also presents the theoretical review highlighting work relevant to the topic explored and researched in this work. Chapter 2 gives specific information about the natural gas pipeline network and relevant information for Turkey. Chapter 3 gives a description of the gas pipeline with its model, which is created by Edgar et al. (1978), methodology, and its mathematical formulation with cost-related functions and constraints, and two solution models to solve the minimum cost problem for network design. Moreover, it also presents a solution strategy for the mathematical formulation and analytical framework of a case of Turkey. Using some relevant results, this chapter also discusses how changes in some of the network parameters would affect the solution of the mathematical problem. Chapter 4 has the same information as chapter 3 about natural gas optimization but the technique and model are different than chapter 3. This model whose creator is Tabkhi et al. (2009) has more effective variables comparing to chapter 3 model. Chapter 5 provides the fundamental definitions and assumptions necessary to formulate and implement a network design and optimization model of the case of the Turkish natural gas pipeline network system. Also it has basic design parameter values for model 2. Chapter 6 presents numerical results related to the

optimization models and to the use of different metrics and aspects to evaluate the whole network with optimal values. Also presented in this chapter are the main results and conclusions of a data gathering effort to evaluate the effects of new optimal network design for Turkish natural gas network system. Chapter 7 provides the comparison between two different optimization models and their results. Chapter 8 includes; suggestions, discussion concluding remarks and directions for future work. This chapter also introduces different and effective suggestions that can be obtained from the results of the minimum cost optimization network problem.

CHAPTER 2

NATURAL GAS PIPELINE SYSTEM

2.1. Pipeline Components

Several parts of equipment compose the pipeline networks. These parts are mainly pipes, compressor stations, metering stations, valves and control stations. Adeyanju and Oyekunle explain the main elements of a pipeline system as following and the pipeline schematic is shown as Figure 6.
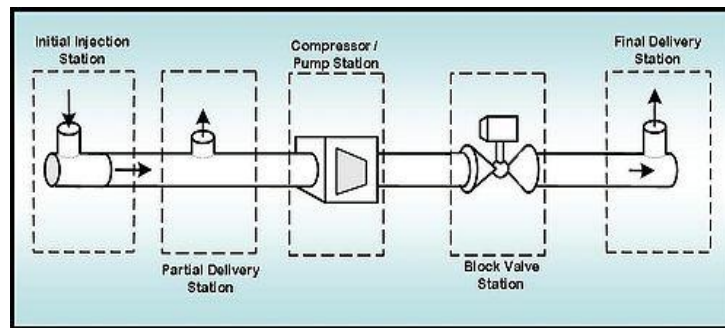
Figure 6. A pipeline schematic (Source: Adeyanju and Oyekunle)

A. Pipes: Consist of strong carbon steel material, to meet the Petroleum Standards. They are covered with a specialized coating to prevent corrosion when paced under ground. Also, their measure is generally between 6 inches to 48 inches in diameter.

B. Compressor & pump stations: For liquid pipelines generally pumps are used while compressors are used for gas pipelines.

C. Partial delivery station: Also called intermediate station. It provides the transportation of natural gas for delivering the products.

D. Block valve station: are using for protecting the pipelines.

E.   Regulator station: For regulation of the pressures. It also is a special type of valve station.

F.   Final delivery station: Also called outlet station or terminal. It helps to distribute products to customers.

United Kingdom	303.300
Canada	160.100
United States	207.400
Russia	108.900
Belgium	354.900
Romania	255.200
Spain	390.400
Kazakhstan	74.400
Turkey	407.300

Figure 7. Natural gas prices in selected countries worldwide as of 2010 and 2011 (in U.S. dollars per 10^7 kilocalories) (Source: Knoema, 2011)

Turkey is taking a place between all the countries in the world with its expensive energy prices according to natural gas, petroleum and gasoline prices. For petroleum and gasoline prices Turkey has the first row while for natural gas Turkey is one of the most expensive countries in the world (see figure 7). Generally, for cost of pipeline and compressor stations and maintenance of these factors, a lot of capital is needed for natural gas. These costs will be more expensive in Turkey according to cost of

construction and energy prices, because a huge amount of natural gas (in percentage) is purchased from other neighbor countries around Turkey. Therefore in order to minimize cost, natural gas transportation processes optimization is necessary for the Turkish natural gas pipeline network system.

2.2. Network Properties and Classification

According to current development in energy infrastructure, natural gas is the most popular energy source with nuclear energy among other energy resources. End users can differentiate the use of gas according to their needs such as in their home or in the industry. For obtaining this gas resource, natural gas is transported over the long distance by having complex tasks from the wellheads as a raw material to be received by the residential or businesses users (as a clean and efficient source of energy, i.e., as we know it). Corresponding to different transitional stages of natural gas these tasks can be classified into two primary groups (Rios-Mercado and Borraz-Sanchez, 2012):

(a) Exploration, drilling, extraction, production and long-term storage of natural gas

(b) Gathering, short-term storage, transportation and distribution of natural gas

In the Turkish natural gas pipeline network system, transitional stages like group (b) have long and complex pipelines and various diameters to meet the complexity of the network and transportation system.

2.3. Transportation of Natural Gas via Pipelines

Since our case is especially related to transmission of natural gas pipeline systems, we will give brief information about the transportation of natural gas in this section. An extensive and well-established transportation system is required from production stage to consumption stage for efficient and effective movement of natural gas. A complex network of pipelines is combined and designed for the natural gas to

transport it quickly, efficiently and effectively from its origin to the last places where the natural gas demand is high.

Natural gas transportation has higher importance for oil and gas industry; so, this transportation should be done efficiently. To transport natural gas, the economic, effective and safe way is to use pipelines.

In the use of natural gas, the most important difficulty is transportation and storage because of the construction during the long distances, large diameters of pipelines and complex infrastructure of the natural gas system. So, in this thesis we focus on especially on the transmission system of natural gas pipeline network. Because if we get optimal, effective and efficient network design including the optimal diameters, pressures, lengths and compressor stations, we can get more efficient future according to energy resources usage rate.

Transportation is also important for the market to meet the demand. By help of pipeline segments, all the points, places and areas can get natural gas to meet their demand. To get an important part in a most competitive market, optimal designed natural gas pipeline network should be obtained in a current global energy market.

To develop well-constructed transportation systems, sufficient capital and investment cost is needed. Pipeline system and compressor stations have the majority of cost for the natural gas transportation. Pipeline lengths and diameter sizes are affecting the cost of pipelines. Also, the pressure factor affects the cost of compressor station (Adeyanju and Oyekunle).

Therefore, to obtain the optimal cost function for the natural gas transmission, which is either minimizing cost or maximizing profit, the appropriate balance between pipeline cost of gas pipeline and compressor cost should be acquired. The cost function is very complex for this aspect. To make it easy to manage and to get more efficient system, optimization of the pipeline network is necessary.

2.4. Natural Gas Transportation Via Pipelines

To transport or move something solid, liquid or gas, the well established transportation system should be set up for perfect supplying, importing and exporting factors. The natural gas transportation is the most important activity to move gas from one point to another. Several types of transportation can be used to transport gas in natural gas industry, but the most effective, economical and efficient way to do this transportation is in pipelines with their complex networks.

Currently, offshore and onshore systems are using pipelines, even though there are differences in terms of security, terrorist attacks and construction prices. For building pipeline network systems under the sea or over the sea is very costly and technically complex. Because of this, generally the companies that are working on pipeline systems are setting the onshore systems in an area where the demand of gas is high to decrease the cost of construction. For example, according to *Gazprom* which is a well-known company and the most powerful company in Europe for natural gas industry, the costs of construction of the onshore pipeline system on Russian and German territory is around 6 billion euro (Dempsey, 2007), the 1220 km long (41 in) *Nord Stream* pipelines is expected to cost around 8.8 billion euro (Nord Stream, 2008).

To analyze the Turkish natural gas pipeline network system, we need to consider the following points. In current aspect, the location, natural gas pipeline system construction and operation are generally managed and controlled by federal and state regulations in Turkey. The Turkish Petroleum Pipeline Corporation (BOTAS) is the governmental and only company for the natural gas industry in Turkey, although in several countries, including USA, Canada, and Brazil, pipeline systems are fully privatized. In these scenarios, fuel cost minimization is the most important factor to give a priority for cost-related optimization techniques. For example, in European countries like Turkey, the compressor stations are located in transmission lines and they are usually run at their maximum capacity for long time periods. So, the placement of compressor stations should have the priority to minimize cost or maximize profit.

Otherwise, moving the compressor stations location from one location to another can be costly and will not be efficient. To prevent this cost-related problem, the transmission system should be constructed well.

Figure 8. Transportation pipelines (Source: BOTAS)

Pipelines are especially used in gathering systems, transmission systems and transmission systems. The diameters of pipelines range between 4 inches and 48 inches (EIA). Raw natural gas is gathered from production wells by the gathering pipeline systems. The mission of these three pipelines are to transport natural gas across the world, to bring natural gas from storage facilities to distribution systems, and to distribute natural gas to homes and to industry.

The main differences among these systems are types and characteristics of pipelines such as diameters, materials, lengths and maximum and minimum pressures. For instance, gathering and transmission lines are constructed from steel pipe (see Figure 8), whereas distribution lines can be constructed from steel or modern plastic pipe.

2.5. Gathering Systems

Gathering line is one of the major three types of pipelines. Low pressure and small diameter pipelines compose the gathering system to help transportation of natural gas from wellhead to the processing plant. Flow lines are composed of narrow pipelines

typically buried 4 feet underground and working at an approximately 250-psi pressure (naturalgas.org).

Small and medium diameters are generally used in gathering systems and transportation systems. Gathering systems are composed of generally medium size steel pipelines which is equal to 18 inches or less and they are working at a nearly 700 psi pressure (naturalgas.org).

2.6. Transmission Systems

A second type of pipelines is transmission line, which is a center of our study. A transmission line is a pipeline that especially used to transport natural gas across long distances from a gathering, processing or storage facility to a distribution system. Transmission pipelines are made of steel, but it can be specialized according to its function and area. Transmission pipelines` diameter measure are generally 6 to 48 inches in diameter, which can vary according to function and task. Mainline transmission pipes are generally between 16 and 48 inches according to diameter sizes while they are between 24 and 36 inches in diameter in major interstates (naturalgas.org).

Compressor stations help pipelines for transporting gas from one point to another point. If there is a large amount of gas to be transported, compressor stations should be installed at strategic points along the transmission lines. Another reason why we did this study is to place optimal number of compressor stations with optimal pipeline diameter, length, pressure and flow rate, because of the above reason according to transportation of large amount of gas and complex pipeline systems in Turkey. These compressor stations usually work at a pressure of approximately 200 psi to 1,400 psi (naturalgas.org).

2.7. Distribution Systems

A third and last type of pipelines is distribution lines, which represent the final step in delivering natural gas to households or industrial customers. They are part of a pipeline network system located downstream of a natural gas transmission line. Because

of this, they are the middle step between high-pressure pipelines and low-pressure pipelines.

Natural gas distribution systems` pipelines are small- to mid-size pipelines, which are ranging from 2 inches to 20 inches in diameter. And they can be constructed of plastic, cast iron, and steel. Distribution pipelines generally operate below their capacity and their working pressure is approximately between 0.5 psi and 200 psi (naturalgas.org). The cause of the lower capacity is security reasons such as terrorist attacks such as in Turkey.

2.8. Technicalities of Gas Transmission Network Components

Compressor Stations

A compressor station, also called a pumping station, is a crucial facility for transporting natural gas. To provide energy, compressor stations compress the natural gas by pumping up its pressure to move the gas through the pipelines.

Figure 9. Compressor station (Source: BOTAS)

Compressor stations are installed along a pipeline route, generally from every 40 miles to 100 miles (naturalgas.org). As mentioned above, compressor stations (see Figure 11) have an important and vital role in the natural gas industry. A simple and basic task of compressor is increasing or adjusting pressure of natural gas by squeezing its molecules. This arrangement of pressure helps the transportation/transmission of natural gas by providing enough energy to natural gas. Compressor stations cover a huge area to set up because of its large mechanical infrastructure.

Compressor stations receive the gas at pressures ranges of 200 psi to 600 psi and compress it back up to 1000 psi to 1400 psi (naturalgas.org). As a result, compressor stations play an important role to transport natural gas to end-users or customers.

2.9. Turkish Natural Gas Pipeline Network System

"Turkey is holding a strategic role in natural gas with its position between the world's second largest natural gas market, the substantial gas reserves of the Caspian Basin, continental Europe and the Middle East", (EIA, Country Analysis page. http://www.eia.gov/countries/cab.cfm?fips=TU*).*

Natural gas is an important and essential energy resource and today its share is apparently increasing among other energy resources because of costs and cleanliness. According to fast development in global natural gas and energy infrastructure, the strategic location of Turkey between Europe and Asia and increasing demand causes Turkey to get involved in and to play an effective role in world`s energy market.

Improvements, developments and technological factors in almost every aspect have made countries more dependent on each other not only locally also globally. Because of its strategic geographical location, Turkey has significant importance and quality with its wide knowledge and experience, deep-rooted history, expansive culture and rich natural and demographic resources.

The length of crude oil pipelines operated by BOTAS, the state gas company in Turkey, has reached 3,332 km (2070,41 miles) (BOTAS, 2011). This length of pipelines transports natural gas to 71 provinces by the end of 2011 through 12,215 km (7590 miles) in Turkey (BOTAS, 2011). The future plan of the company is to supply natural gas to all cities after the completion of ongoing transmission and distribution lines (see table 4).

Table 4. Natural gas purchase contracts and ongoing transmission and distribution lines in Turkey (Source: Botas, http://www.botas.gov.tr)

Current Agreements	Supply (billion m^3/year)	Signature Date	Duration (year)	Completion Date
Algeria (LNG)	4	1988	20	2008
Nigeria (LNG)	1.2	1995	22	2017
Iran	10	1996	25	2021
Russian Fed. (Blue Stream)	16	1997	25	2022
Russian Fed. (West)	8	1998	23	2021
Turkmenistan	16	1999	30	2029
Azerbaijan	6.6	2001	15	2016

In Turkey the demand of energy started to increase in the 1980`s because of the population growth and fast industrialization. These factors and usage of coal to produce energy also have caused some crucial problems such as air pollution as the first consideration. To solve these problems and in order to meet the demand of energy with the natural gas as an alternative clean energy source, Turkey made an agreement with the

Union of Soviet Socialist Republics (USSR) about the delivery of natural gas on September 18, 1984 and February 14, 1986 between the Turkish Petroleum Pipeline Corporation (BOTAS) and SOYUZGAZ EXPORT which is an organization from USSR authorized on natural gas trade as a solution of these considered problems and to supply demand of natural gas in some cities (Botas, 2011). After the first purchase agreement with USSR, other purchase agreements which are shown in table 4, were made to meet increasing demand for natural gas in Turkey.

After these purchase and sale agreement (see table 4), the 842 km (523 miles) long Russian Federation-Turkey Natural Gas Pipeline started to be constructed on October 26, 1986, and entered Turkey at the location of Malkoclar on the Turkey-Bulgaria border, reaching Hamitabat on June 23, 1987, and then followed the route of Ambarlı, Istanbul, Izmit, Bursa, and Eskisehir finally reached Ankara in August, 1988 (EMRA, 2011). For usage for residential and commercial sectors natural gas was supplied in October, 1988 to Ankara, in January, 1992, to Istanbul, in December, 1992, to Bursa, in September, 1996 to Izmit and in October, 1996 to Eskisehir (EMRA, 2011).
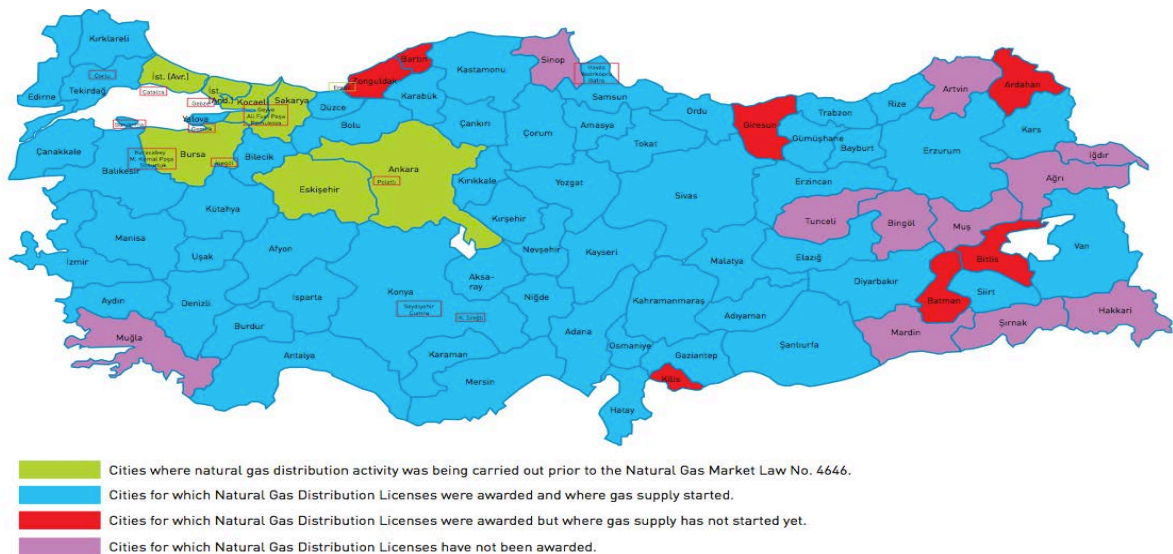
Figure 10. Map of natural gas distribution activities (Source: EMRA Annual Report, 2011)

Figure 10 shows cities where natural gas distribution infrastructure is in progress, is currently continuing or has not been started.

At the first time when natural gas was introduced in Turkey in the 1970's, some important conditions made the import of natural gas mandatory for Turkey in order to meet the current and potential demand of natural gas. Table 5 shows the imports of natural gas between 2005-2011 by country.

As may be seen from Table 5, Turkey is substantially dependent on import to supply natural gas and particularly dependent on Russia for the import of a huge amount of natural gas.

Table 5. Natural gas imports between 2005-2011 (million sm^3, million standard cubic meter) (Source: EMRA, 2011)

Years	Russia	Iran	Azerbaijan	Algeria	Nigeria	Spot LNG	Total
2005	17.524	4.248	0	3.786	1.013	0	26.571
2006	19.316	5.594	0	4.132	1.100	79	30.221
2007	22.762	6.054	1.258	4.205	1.396	167	35.842
2008	23.159	4.113	4.580	4.148	1.017	333	37.350
2009	19.473	5.252	4.960	4.487	903	781	35.856
2010	17.576	7.765	4.521	3.906	1.189	3.079	38.036
2011	25.406	8.190	3.806	4.156	1.248	1.069	43.874

2.10. The Pipeline Configuration of Turkish Natural Gas System

The major amount of natural gas is coming from Russia with the Blue Stream Pipeline and Westward pipelines. The Blue Stream pipeline agreement is a very new agreement with Russia. Because of the ongoing construction of this Blue Stream pipeline system, the major amount of gas reaches the big cities that have populations above 350,000 such as Istanbul and Bursa via the Bulgaria-Turkey line namely Westward pipelines. The importation rate in total is 890 Bcf of natural gas, which is obtained from Russia in 2011 (BOTAS, 2011).
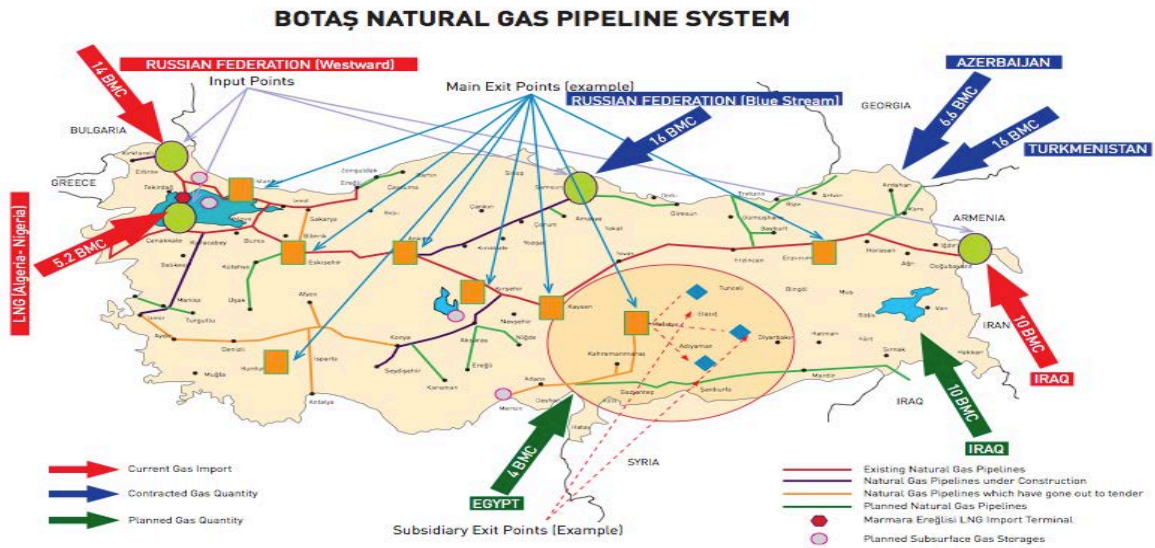
Figure 11. Pipeline Configuration on a Map (Source: BOTAS Annual Report, 2011)

Iranian natural gas, which is imported from Iran via Tabriz-Dogubeyazit pipeline system, is supplying about 290 Bcf in 2011 (BOTAS, 2011). Also, Turkey receives approximately 140 Bcf of natural gas from another entrance point of Azerbaijan through the BTE pipeline in 2011 (BOTAS, 2011).

Turkey is a transit country of natural gas pipelines between Europe and Middle East. Besides this, Turkey has to import enough amount of natural gas to supply both domestic and industrial demand of energy. The strategic position of Turkey and its location between the countries help Turkey to meet domestic demand with these pipelines although the price of gas is so expensive.

As a summary, in the future, the strategic and effective position of Turkey as a gas transit state will affect its need of natural gas to satisfy rapidly growing domestic consumption of energy.

Figures 11 and 12 give the big picture about: main entrance and exit points, main transmission lines, current pipeline segments, natural gas pipelines under construction,

planned gas pipelines, compressor stations and whole map of Turkish natural gas network system.
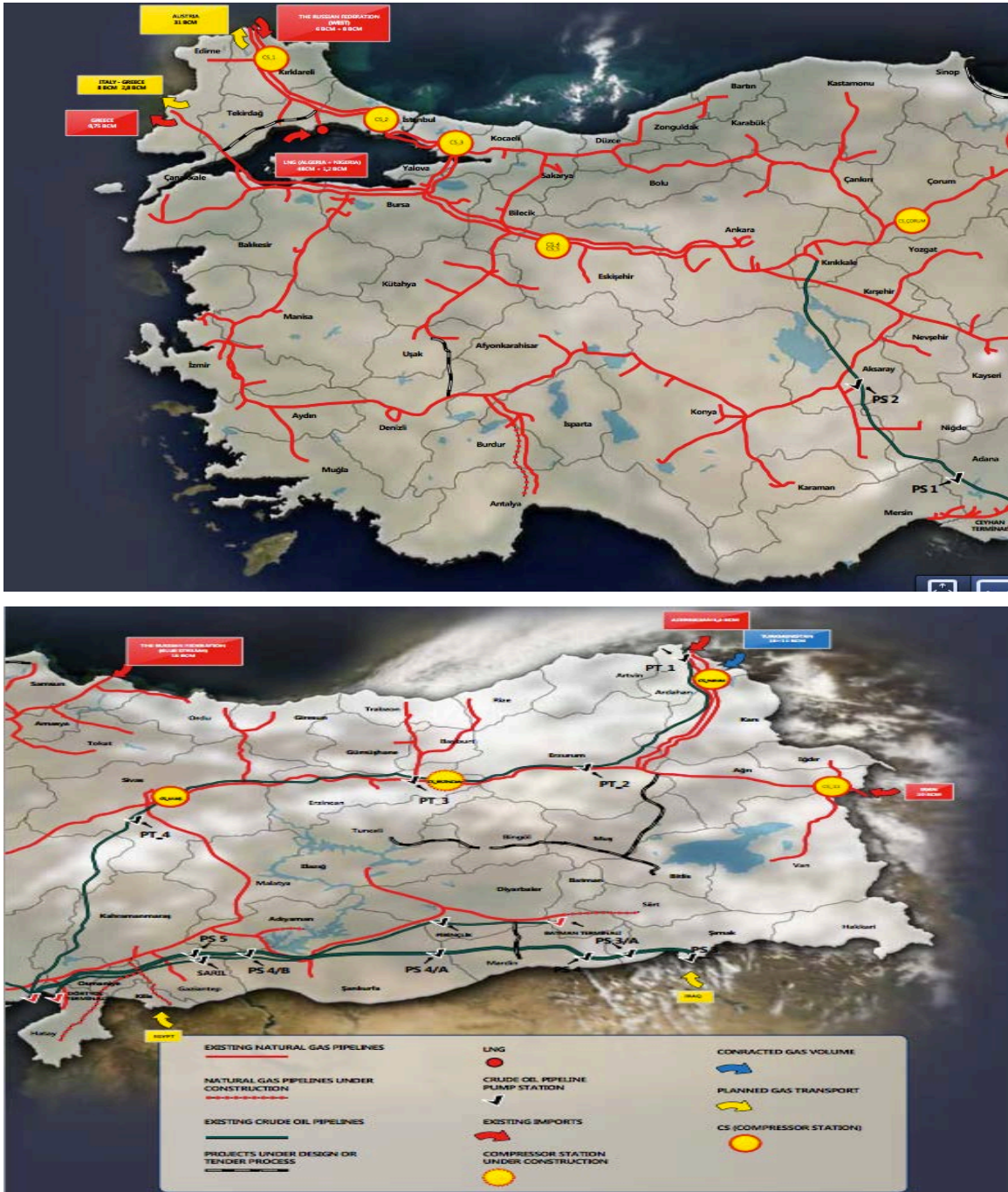
Figure 12. Natural gas and crude oil pipeline system of BOTAS (Source: Annual Report, 2010)

CHAPTER 3

MODEL 1 DEVELOPMENT, MATHEMATICAL FORMULATION AND SOLUTION STRATEGY

Source of gas, pipeline segments with arcs, compressor stations and delivery points constitute a gas gathering and transmission system. To design or expand a gas pipeline transmission system, maintenance costs and especially operating costs should be considered. These factors that have to be considered are (Edgar et al., 2001):

a. The maximum number of compressor stations that are required and are being considered for the optimization

b. The gas in the pipelines and the compressor stations` operating pressures

c. The optimal locations of these compressor stations

d. The initial construction dates of the stations

e. The optimal size of diameters, thicknesses, and lengths of pipes on each arc of the network

f. The optimal solution for expanding the compressor stations

g. The optimal size of diameters for the main pipes

The formulation of the problem presented in this section applies to a situation where the gas pipeline system is designed and its topology is chosen as in the current system of Turkish natural gas network and transmission system. So, a prespecified quantity of natural gas per time from point A to any other points are transported via these pipelines with its current design. The initial state with pressure, temperature and composition at point A and final states of the gas are known. In our case study for Turkey, some of the above factors already currently exist in Turkish natural gas system and various factors

involved are clear. After considering this statement, we need to determine:

- The compressor station (CS) quantity

- Length of the pipeline segments between CS

- Diameter sizes of pipeline segments

- The pressures at each compressor station

The minimum total cost per year including capital, operating and maintenance costs are aimed to be the criteria for the optimal design of the pipeline network. This problem does not consider fixed the main variables, which are listed above.

To get the picture of this model and problem, we have to analyze two related problems; one of them has much harder degree than the other one. Edgar *et al.* (2001 p. 474) mention these differences as the following: " when the compressor capital costs are linear function of horsepower, continuous nonlinear programming problem can be applied to solve the transmission problem. On the other hand, if there is a capital costs has the fixed capital cost, then the problem will be more realistic case." The second one is closer to our case problem for Turkish network system. As a result of this, the network design problem is becoming harder to solve by using a branch-and-bound technique to decide whether there should be compressor station or not, with using a nonlinear programming algorithm.

The following sections give a description of the pipeline network optimization model. We used the mathematical optimization software called GAMS (General Algebraic Modeling System - www.gams.com) to apply this model to Turkish Natural Gas pipeline network system.

We can divide the discussion of the transmission line problem into five parts: (1) the pipeline configuration, (2) the variables, (3) the objective function and costs, (4) the

inequality constraints, and (5) the equality constraints.
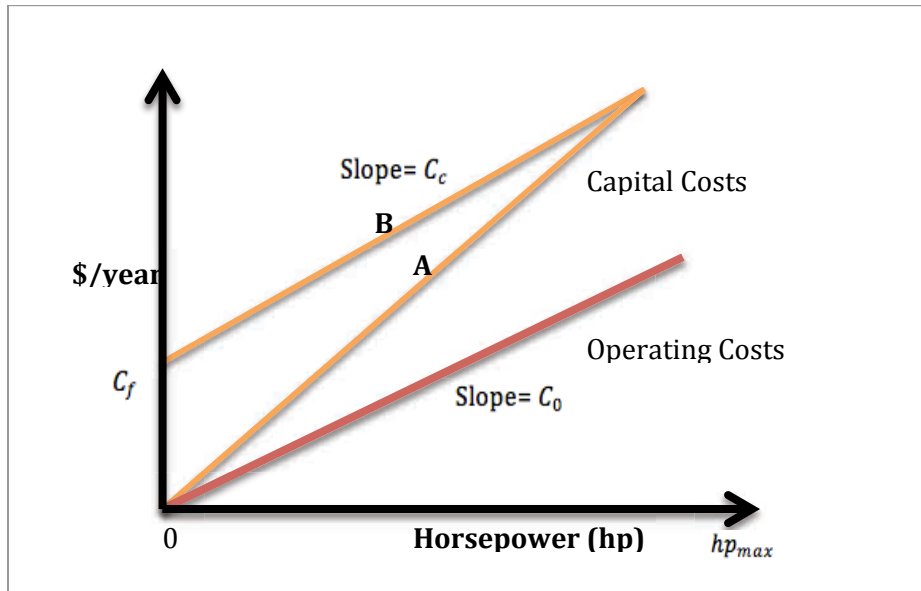
Figure 13. Capital and operating cost of compressors (Source: Edgar et al., 2001)

3.1. Pipeline Configuration

The pipeline configuration is assumed as given. In chapter 5, the topology of the Turkish natural gas network transmission system is described. A node represents a compressor station and an arc represents a pipeline segment. It is assumed that pressures are increasing at compressors while they are decreasing along the pipeline segments. In our case the transmission line is also horizontal and generally the transmission line is horizontal in many countries. However, it can be vertical but in these systems the way of suction and discharge pressures can change, so the system can be affected by these factors.

3.2. Decision Variables

To define the problem with the decision variables, objective function, equality and inequality constraints, we will use the example of the pipeline network shown in figure 10 with three branches. After section 3, we will re-arrange these model variables

according to Turkish natural gas pipeline network system in section 4.

Parameters

γ	= ratio of specific heats
z	= compressibility factor (in suction condition same as model 2)
T_1	= suction temperature
K_i	= prespecified maximum limit
0.08531	= conversion factor from kilowatt to horsepower
n	= # of compressors in the system (represented by nodes)
m	= # of pipeline segments in the system (represented by arcs)
C_0	= annual operating cost , \$/(hp) (year)
C_c	= capital cost of compressor, \$/ (hp) (year)
C_s	= capital cost of pipeline, \$/ (in) (mile) (year)
C_f	= fixed initial cost of compressors (\$)
$p_{d_i}^{min}$	= minimum inlet pressure
$p_{d_i}^{max}$	= maximum inlet pressure
$p_{s_i}^{min}$	= minimum outlet pressure
$p_{s_i}^{max}$	= maximum outlet pressure
D_i^{min}	= minimum diameter of segment
D_i^{max}	= maximum diameter of segment
L_i^{min}	= minimum length of segment
L_i^{max}	= maximum length of segment
L_k^*	= length of a branch

Decision Variables

W_i	= rate of work, horsepower
b_i	= compressor decision (binary variable)

- b_i= 1, if compressor installed,

- $b_i = 0$, otherwise.
- $b_i = \{0,1\}$

p_{d_i} = inlet pressure (psi)

p_{s_i} = outlet pressure (psi)

Q_j = flow rate ($kwatt$/h)

D_j = pipeline diameter (inch), (can be different in each segment j)

L_j = pipeline segment length (mile), (for each segment j)
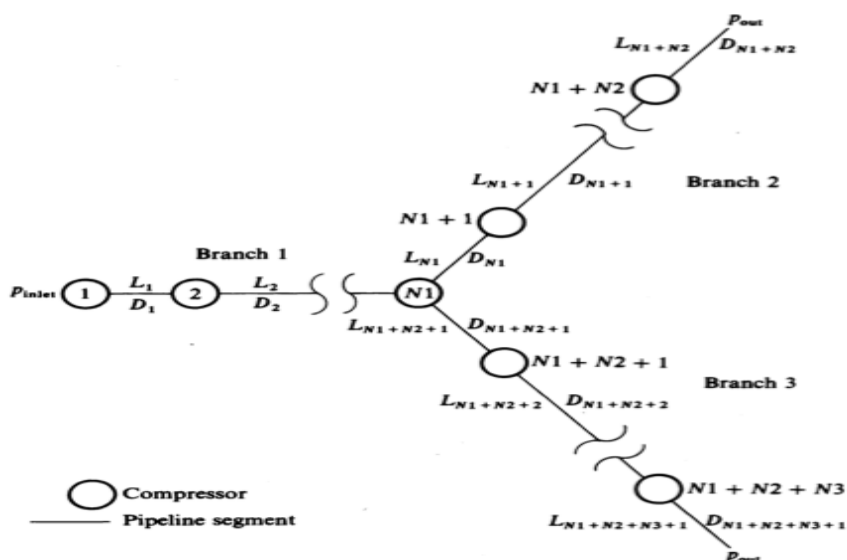
Figure 14. Example of pipeline configuration with three branches (source: Edgar *et al.* 2001)

For the example above (see figure 14) for a given configuration of pipeline, each node and each arc are marked in separately. N1, N2, N3 and… Nn (see figure 14) represent the maximum number of possible stations in each of the branches. The number for variables is shown as following:

- n   : Total number of possible compressors (n= $\sum Ni$)
- n-1   : Suction Pressure (the initial entering pressure is known)

- n　　: Discharge Pressure
- m　　: Diameters
- m　　: Lengths
- m　　: Flow rates

3.3. Objective Function

The goal of this optimization is to minimize the cost of operation and maintenance costs of compressors and capital cost of the pipeline segments and compressors. Objective function are defined by Edgar et al. (2001) as the sum of the yearly costs of operating and maintenance of compressors plus the sum of the pipeline segments` and compressors` capital costs which is annualized over a period of 10 years. Pipe diameter and lengths are a part of this annualized costs for each pipe segment.

The work rate for a compressor is:

$$\text{W} (p_{d_i}, p_{s_i}) = (0.08531) Q \, T_1 \frac{\gamma}{\gamma-1} \left[\left(\frac{p_{d_i}}{p_{s_i}} \right)^{\frac{z(\gamma-1)}{\gamma}} - 1 \right] \tag{1}$$

The objective function is (if fixed capital cost for compressors are zero):

$$\text{Min} \sum_{i=1}^{n} (C_0 + C_c) \, \text{W} (p_{d_i}, p_{s_i}) + \sum_{j=1}^{m} C_s L_j D_j \tag{2}$$

If all the costs are fixed compressor costs, our objective function will be:

$$\text{Min} \sum_{i=1}^{n} ((C_0 + C_c) * \text{W} (p_{d_i}, p_{s_i}) + (C_f * b_i)) + \sum_{j=1}^{m} C_s L_j D_j \tag{3}$$

Note that n, m, C_0, C_c, C_f and C_s are fixed according to our case given values. The cost parameters C_0, C_c and C_s are same for all of the five pipeline segments (according to entrance points), even though n and m are changing as the number of

compressors and pipeline segments for the five different pipeline networks. Also, b_i is changing according to compressor decision on the network.

Because of the limitations of nonlinear programming algorithm a branch and bound (BB) technique should be used and applied to this model to solve it more properly (Edgar et al. 1978). It is not needed to use BB technique if capital costs follow line A in figure 15, which is not a realistic case. But for line B a branch and bound technique must be used and applied to case with the nonlinear algorithm to get the more realistic results.

3.4. Inequality Constraints

These are constraints are for operation of each compressor. The suction pressure should be lower than or equal to the discharge pressure as shown in the following equation:

$$p_{d_i} \geq p_{s_i} \qquad\qquad \text{i=1,....,n} \qquad\qquad (4)$$

and the compression ratio does not exceed assigned limit K which is a maximum value,

$$p_{d_i} \leq K_i\, p_{s_i} \qquad\qquad \text{i=1,....,n} \qquad\qquad (5)$$

Moreover, the lower and upper bounds are placed on each of the four variables

$$p_{d_i}^{min} \leq p_{d_i} \leq p_{d_i}^{max} \qquad\qquad \text{i=1,....,n} \qquad\qquad (6)$$

$$p_{s_i}^{min} \leq p_{s_i} \leq p_{s_i}^{max} \qquad\qquad \text{i=1,....,n} \qquad\qquad (7)$$

$$L_i^{min} \leq L_i \leq L_i^{max} \qquad\qquad \text{i=1,....,n} \qquad\qquad (8)$$

$$D_i^{min} \leq D_i \leq D_i^{max} \qquad\qquad \text{i=1,....,n} \qquad\qquad (9)$$

3.5. Equality Constraints

For this chosen gas transmission network problem, two different classes of equality constraints exist. One of them is that the length of the system is fixed (note that the pipeline segment`s length is not fixed). For example, in the configuration of figure 13;

$$\sum_{j=1}^{N1-1} L_j + \sum_{j=N1}^{N1+N2} L_j = L_1^* \qquad\qquad (10)$$

$$\sum_{j=1}^{N1-1} L_j + \sum_{i=N1+N2+1}^{N1+N2+N3+1} L_j = L_2^* \tag{11}$$

where L_k^* represents the length of a branch. Also, the lengths of all the branches are fixed. Second class of equality constraints is the flow equation, which means that the Weymouth flow equation should be satisfied by each pipeline segment (GPSA, 1972):

$$Q_j = 871 \, D_j^{\frac{8}{3}} \left[\left(\frac{p_{d_j}^2 - p_{s_j}^2}{L_j} \right)^{\frac{1}{2}} \right] \qquad \text{j=1,....,m} \tag{12}$$

p_{d_j} = entrance point discharge pressure

p_{s_j} =exit point suction pressure

     The above equations are re-arranged according to an exact model of the Turkish natural gas network. For avoiding taking square roots in equation (12), equation (13) can be used:

$$871^2 D_j^{\frac{16}{3}} (p_{d_j}^2 - p_{s_j}^2) - L_j Q_j^2 = 0 \tag{13}$$

With considering above explanations, the problem is to minimize equation (3) subject to constraints (4)- (11), (13).

3.6. Solution Strategy

    For this problem, we give two different solution techniques as mentioned before. If there are no fixed capital costs, then we can solve it directly by using a nonlinear programming algorithm.

    As Turkish Natural Gas network system is an example of real life experienced company, we should use branch and bound algorithm with non-linear algorithm to solve this problem and get the optimal solution. The reason why we should use the algorithms,

mentioned above is that: if the capital costs includes a fixed component, then nonlinear programming in conjunction with branch-and-bound enumeration must be used to accommodate the integer variables for compressors being in place or not.

We can determine the partition variable according to procedure explained by Edgar et al. (1978, p.475) as; "*the smallest average compression ratio of all the branches can be calculated by adding all the compressor ratios in each branch in the transmission system and then it can be divided by the number of compressors in the branch. If this procedure is used and applied then the number of compressors which has smallest ratios in the branch will be the partition variable.*" After we select the partition variable, then we need to determine how this partition can be done for variable. If the compressor operating capacity is less than 10% and it means there is no compressor needed to construct in the line (Edgar et al., 1978). After this, if the operation capacity of compressor stations is greater than 10%, we need to delete the compressor, which has the smallest compression ratio (Edgar et al. 1978).

Edgar et al. (2009) states that the search toward the branch should be continuous, if the value of objective function at a node is greater than the best feasible solution: This process is continuing backward to up the tree until searching of all nodes in the tree have been done into the node. The best solution that is found will be the solution to the whole problem at the end of this procedure and search (Edgar et al. 1978).

CHAPTER 4

MODEL 2 DEVELOPMENT, MATHEMATICAL FORMULATION AND

SOLUTION STRATEGY

This model is also related to design properties of the pipelines, but it considers a different and more current model and formulations to find the design properties of pipeline system and needed compressor stations for satisfying customer demands with using available supply & storage gas capacities.

Tabkhi et al. (2009) present two different ways for this optimization problem:

1) In the former case, the pipeline diameters are considered as continuous variables all along the problem solution strategy, and corrected after optimization procedure by rounding them up to the closest commercial size used in practice.

2) In the latter case, which is more realistic, logic and current constraints are considered into the constraint set of the MINLP problem, to force the pipeline diameters to their commercial sizes during the optimization procedure.

4.1 Decision Variables

To define the problem with decision variables, we will use the same data from Turkish Petroleum Pipeline Corporation and the current map of natural gas pipeline system. Our main idea is to compare the results of model 2 with the results of model 1 by using the same decision variables-related results which are pressures, flow rates, lengths, diameter sizes and number of compressor stations, mainly. The other decision variables, which are different than model 1, are listed below. Tabkhi et al. (2009) tried to consider all the factors that can affect the network design and system to find the more optimal results comparing with the model 1. By considering whole model of model 2, we divide the decision variables into two main parts, which are shown below (Tabkhi et al. 2009):

Design Properties of Pipelines

- Pipe diameters

- Pressures at nodes (MAOP calculation)

- Gas flow rates

- Wall thickness

Characteristics of Compressor Stations

- Location of the compressor stations

- Suction pressure

- Pressure ratio at CS

- Station throughput

- Fuel consumption rate at compressor stations

- Power consumption of station

- Required number of compressor stations

-Average gas velocity through pipe

d_j = pipe diameter (m)

L_j = pipeline segment length (km)

$maop_j$ = maximum allowable operating pressure (bar)

t_j = wall thickness (m)

P_j = power consumption of CS (hp)

$mlnc_i$ = material balance around node i (kg/s)

m_j = flow rate (kg/s)

mc_j = mass flow rate of compressed gas (kg/s)

prt_j = pressure ratio

V_{e_j} = average gas velocity (m/s)

h_{i_j} = compressor isentropic head (m)

m_{f_j} = flow rate of consumed gas in each CS (g/s)

b_i = compressor decision (power related binary variable)

- b_i= 1, if compressor installed,

- $b_i = 0$, otherwise.
- $b_i = \{0,1\}$

4.2 Parameters

C_0	= annual operating cost , \$/(kwatt) (year)
C_c	= capital cost of compressor, \$/ (kwatt) (year)
C_s	= capital cost of pipe, \$/ (km) (m) (year)
C_f	= fixed initial cost of compressors (\$)
k	= isentropic exponent
Z	= compressibility factor of gas
$Temp$	= temperature (K)
$smys$	= specified minimum yield strength
f_F	= design factor
f_E	= seam joint factor
f_T	= temperature factor
R	= universal gas constant (J per kmol K)
Mol	= average molecular mass of gas (g per mol)
LHV	= low heating value
S_i	= amount of gas to be delivered
η_i	= compressor isentropic efficiency
η_m	= mechanical efficiency
η_d	= driver efficiency

According to Tabkhi et al. (2009), some assumptions are made according to general natural gas systems and literature. These assumptions and some given values for parameters are shown in table 6 below. We used some of these values between the magnitudes shown below according to Turkish natural gas network system. Our case related parameter values are shown in section 5.8.

Parameter	Order of Magnitude	Unit
Average molecular mass of gas	18-25	g/mol
Gas critical pressure	45-50	bar
Critical temperature	200-250	K
Gas isentropic exponents	1.2-1.4	-
Specified Minimum Yield Strength	2000-5000	bar
Design factor	0.4-0.7	-
Network temperature	260-315	K
Compressor mechanical efficiency	80-98	%
Seam joint factor	0.6-1.0	-
Compressor driver efficiency	25-45	%

Table 6. Parameter values for Model 2 (Tabkhi et al. 2009)

4.3 Objective Function

The aim of this optimization is to minimize total annual cost, which includes the sum of the investment cost in 10 years and the operating annual cost as in model 1 by Edgar et al. (1978). Also we have *n* nodes, *l* pipe arcs and *m* compressor arcs & fuel stream arcs. So, because of these arcs, we use the subsets to divide them into their arc-representation parts.

$$\textbf{ATC} = \sum_{j \in arcs}(\textbf{ICP}_j + \textbf{ICS}_j + \textbf{OCS}_j)$$

ATC   =Annualized total cost ($/year)

$$\textbf{ICP}_j = (C_s \textbf{dL})_j$$

ICP_j = investment cost of pipelines

$$\textbf{ICS}_j = (C_f \textbf{sgn}(\textbf{P}) + C_b \textbf{P})_j$$

ICS_j = investment cost of compressors

sgn (P)   = the sign of a real number (0 or 1; if compressor station horsepower is=0, then ICS =0)

If no compressor exists on an arc, its related horsepower, namely the term ICS_j, will be equal to zero, because of the sign function of powers. Also, the other cause of this factor is that; if there is no compressor station, there will not be a compressor station, so

there will not occur power consumption in that CS. As a result of this, investment cost of compressors will be zero. We consider operating and maintenance costs because of the compressor stations. It is assumed that pipelines have no operating costs in this model.

$$\textbf{OCS}_j = (\textbf{\textit{C}}_o\textbf{\textit{P}})_j$$

OCS_j = yearly operating cost (euro/kw year)

4.4 Constraint Definition

First of all, the pressures of the pipelines should provide the limit of the maximum value, which is less than the maximum allowable operating pressure (MAOP) (Tabkhi et al. 2009). This is one of the variables and design parameters in our model.

$p < \text{MAOP}$

p = pressure (bar)

$$MAOP_j = \text{SMYS} \frac{2t_j}{d_j - t_j} f_F f_E f_T$$

Specified minimum yield strength (SMYS) should be 2000 bars for used steel according to pipeline engineering terms.

f_E : between 0.6 and 1 (assumed 1)

f_F : 0.4 (low enough and safe value) (depends also on population density)

f_T : equal to 1 for gas temperatures below 120 C

According to Tabkhi et al. (2009); to calculate Maximum Admissible Operating Pressure (MAOP) for each pipeline requires its wall thickness, which can be obtained by using the equation below.

$$t_j = 52*10^{-3}d_j + 989 * 10^{-7}$$

To calculate the material balance around node *i* following equation should be used:

$$\sum_{j \in arcs}[a_{i,j}m_j(2b_j - 1) - m_{cj}(a_{i,j}(2b_j - 1) - 1)/2] = S_i$$

b_j represents the flow direction in the original model. But in our case all of the flow direction is considered one way so it should be 1. The equation that I used is shown below:

$$\sum_{j \in arcs}[a_{i,j}m_j - m_{cj}(a_{i,j} - 1)/2] = S_i$$

If the pressure ratio is more than 1, we can decide the existence of a compressor station on an arc. Pressure ratio can be obtained using following equation where p_1 and p_2 are compressor station end-point pressures. Note that, if $b_j =1$ then p_1 and p_2 will be suction and discharge pressures, respectively (Tabkhi et al. 2009).

Pressure Ratio (prt_j) $= b_j\ (\frac{p_2}{p_1})+(1-b_j)\ (\frac{p_1}{p_2})$, $\qquad 1\leq prt_j \leq 2$

In our case $(b_j =1)$: $prt_j = \frac{p_2}{p_1}$, $\qquad 1\leq prt_j \leq 2$

Compressor Isentropic Head Calculation:

$h_i = \frac{Z_s R T_s}{M}\ \frac{k}{k-1}\ [(\frac{p_d}{p_s})^{k(-1)/k}-1]$

Gas consumption rate in a station:

$$m_f = \frac{10^6\ m_c\ h_i}{\eta_i \eta_m \eta_d LHV}$$

Power calculation:

$\text{P} = \frac{m_c\ h_i}{\eta_i}$

Total efficiency means that the products of three values considering isentropic, mechanical and driver efficiencies. Tabkhi et al. (2009) points out that if a compressor station must be considered on a line, it must work with a power greater than a lower value, which is 1000 kW. It can be shown as the following relation:

P=0 v $\qquad P_- \leq \text{P} \leq P^+ \qquad\qquad P_- \neq 0$

Average gas velocity through pipelines is calculated by using the equations below:

$$v_e = 122\ \sqrt{\frac{ZRT}{PM}}$$

In this optimization model, we have two different incidence matrices are considered to define the relation between the variables of the system. In model 2; each compressor, each fuel stream and each pipe are defined by an arc (Tabkhi et al. 2009).

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First matrix, called A and node incidence matrix is a matrix with the dimension of n*
(l+m). Also this matrix makes easier to describe material balance around all the nodes.
Each of its elements, a_{ij} is given by (Tabkhi et al. 2009);

$$a_{ij} = \begin{cases} 1 & if\ arc\ j\ comes\ out\ from\ node\ i \\ -1 & if\ arc\ j\ goes\ into\ node\ i \\ 0 & otherwise \end{cases}$$

Second matrix is called pipe- compressor matrix with the dimension of l*m
whose elements is b_{ij} which is defined below:

$$b_{ij} = \begin{cases} 1 & if\ pipe\ i\ is\ connected\ to\ discharge\ node\ of\ compressor\ j \\ -1 & if\ pipe\ i\ is\ connected\ to\ suction\ node\ of\ compressor\ j \\ 0 & otherwise \end{cases}$$

For programming software we used the GAMS environment to solve our MINLP
problem same as the first model, whose author is Edgar et al. (1978).

With considering above explanations, the problem is to minimize annualized
total cost (ATC) subject to constraints MAOP calculation, material balance, wall
thickness, pressure ratio, compressor isentropic head calculation, power calculation, gas
consumption rate calculation and gas velocity calculations.

CHAPTER 5

CASE STUDY

5.1. Overview (Country Analysis of Turkey)

Turkey is located between the natural gas rich and higher-demand countries in the world. Middle East and Russia are very popular with their natural gas sources while Europe`s demand of natural gas and energy is incrementally increasing. Turkey`s position is in between these countries and regions. So, Turkey has very significant importance in the world according to natural gas, namely energy transportation between the regions.

Natural gas reserves are estimated about 218 billion cubic feet (Bcf) in Turkey by the Oil & Gas Journal in January 1, 2013 while production of natural gas by Turkey is 27 Bcf in 2011 (EIA). Energy demand of Turkey is growing fast and it is among the fastest growth rate in the world in 2010 and 2011 (EIA). Natural gas is an important and most-used energy sources in Turkey. It is indicated by EIA that consumption of natural gas is 0.3 quadrillion British thermal units greater than consumption of oil and coal in Turkey. Turkey`s production rate of natural gas is very small with the total production of 27 billion cubic feet (Bcf) in 2011 (EMRA, 2011). Marmara North and an offshore field in the Sea of Marmara in the Thrace-Gallipoli Basin are the largest gas fields among 14 gas fields in Turkey (EMRA, 2011).

Natural gas sector is controlled and managed by the state-owned Petroleum Pipeline Corporation (BOTAS) in Turkey, even though natural gas market is open to competition within country. Government of Turkey is trying to make the natural gas sector more competitive and they started to open this energy sector market to private companies last year in 2012. However natural gas operation pipelines, infrastructure and network system is built by BOTAS in Turkey and the wholesale market, import and export activities are also controlled by the same state company of BOTAS. Also, BOTAS has been controlling and leading the general natural gas market for decades in

Turkey (EIA). Starting from year of 2011, Turkish government let other companies to mandate the Turkish states` natural gas market to develop the Turkish pipeline networks.

Moreover, to provide adequate and enough supply to domestic market, BOTAS is working on participating and making a new agreements in international natural gas pipeline projects by using the advantage of location of Turkey as a crucial and powerful corridor between Asia, Middle East and Europe to play an active role for transporting of regional energy supply (EIA).

Several government intuitions, which are the Ministry of Energy and Natural Resources (MENR) and Energy Markets Regulatory Authority (EMRA), are responsible for natural gas sector in Turkey (EIA). MENR assigned to be responsible to formulate and implement energy policies with the coordination of both public and private sectors. Turkish Petroleum Corporation (TPAO), BP, and Shell are responsible for producing and taking natural gas out from the ground in Turkey with having permission from the government of Turkey.

In Turkey natural gas is imported via pipelines mainly and mostly from Russia, Azerbaijan, Iran and also from Nigeria& Algeria as liquefied natural gas (LNG) (BOTAS, 2011). LNG can also be imported from the countries of Qatar, Egypt and Norway after the completion of the current projects about pipelines. Beside these pipelines, there are some proposed projects for natural gas pipeline where Turkey seems to play an important role. However none of these projects have started yet. Some of the proposed pipelines are listed as shown above by EIA:

- Nabucco Pipeline: Proposed but delayed project from border of Turkey & Bulgaria to Austria. Its estimated capacity is 1.1 Tcf of gas per day through the countries of Turkey, Romania, Hungary, Bulgaria and Romania to Austria (EIA).
- South East European Pipeline (SEEP): It is the proposed project by British Petroleum. This is much current project so, details of this project is quite low now.

SEEP project needs only 800 miles of pipeline construction to be done. Also, this project is important because its capacity can exceed the capacity of Nabucco`s estimated capacity.

- Trans Anatolian Pipeline (TANAP): It is an alternative project for the delayed project of Nabucco. This pipeline project`s capacity is estimated to be 30 billion cubic meters per year.

- Turkey-Iraq Pipeline: It can be a way for Turkey to get natural gas from Iraq.

5.2. Assumptions and Given Values

The following cost-related values (see table 7) are obtained from Turkish Petroleum Pipeline Corporations (BOTAS) and the assumptions, which are related to our model and needed for it. There are five entrance points and whole network can be decomposed into five sub networks.

- Each compressor is not losing or gaining heat because of it adiabatic situation.
- The flowing gas in the pipeline is isothermal and temperature is constant (assumed 581.67 °R=323.15 °K= 50 °C).
- The gas compressibility factor z is constant before and after passing through the compressor.

Table 7. Cost Values for Turkish Natural Gas Pipeline System

Entrance Points	Russia (West)	Iran	Russia (Blue Stream)	Azerbaijan	Nigeria & Algeria (LNG)
Compressor Capital Cost (C_c)($/(hp)(year))	686	686	686	686	686
Compressor Fixed Cost (C_f) ($)	44450	44450	44450	44450	44450
Pipe Capital Cost (C_s)($/(in)(mile)(year))	9570	9570	9570	9570	9570
Annual Operating Cost (C_0) ($/(hp)(year))	92	92	92	92	92

- It is assumed that each of the compressors is assumed to have gas consumed for operation of one-half of one percent of the gas transmitted (Edgar et al. 1978).

In this study, B&B technique is used to solve our case problem, because of that Turkish Natural Gas network systems is more realistic and all data are obtained from the real life operations.

5.3. Characteristics and Features of Turkish Natural Gas Network System

Some features and characteristics of the case of Turkey according to its current natural gas network system are listed below:

- Main distribution and control center is located in Yapracik, Ankara, Turkey
- Maximum pressure: 75 psi, minimum pressure: 37 psi
- There are 5 different entrance points and we divided whole network into five sub networks and analyzed them separately
- The number of cities with access to natural gas has reached to 71 within total 81 cities, after supplying Batman, Mugla, Hatay and Siirt with natural gas.

5.4. Model Definition for Model 1 and Model 2 of Turkey

The following formulations are formed according to Turkish natural gas network pipeline system and its specific values.

γ = assumed to be 1.32 (Ref: Ratios of specific heat information)

z = ranges from 0.88 to 0.92

T_1 = 50 °C = 122 °F = 581.67 °R

Because of that our case is a real-life and more realistic problem, the objective function is given in equation (3) in chapter 3.

Because of the similarity between the two natural gas pipeline optimization problems and models, we used the same parameters to solve and to optimize Turkish natural gas pipeline system.

The parameters n, m, C_0, C_c, C_f and C_s are fixed according to the our model given values. C_0, C_c and C_s are same for all of the five pipeline segments as mentioned above. For our realistic case problem, we need to add the fixed cost for each compressor in the system at the level of zero horsepower (C_f) to the cost of compressor.

Inequality constraints for Turkish natural gas pipeline network system will be the same as in Chapter 3. But, the equality constraints should be changed to arrange the length of the system according to Turkey. For our case problem about Turkish natural gas network, there are 5 entrance points and totally 12 braches exist. These entrance points are from: five branches from the entrance point of Russia (westward), 4 branches from Iran entrance, and one branch for the each entrance points of Nigeria & Algeria, Russia (Blue Stream) and Azerbaijan.

With twelve branches there are 12 constraints where all the entrance points are solved separately (so the L_j^* values of all five pipeline networks have different values according to length bounds, which are given in table 8, also see table 10 to 19 for detailed lengths) (see Appendix B):

For Russia (westward) Entrance Point:

$$\sum_{j=1}^{5} L_j = L_1^* \tag{14}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{9} L_j = L_2^* \tag{15}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{7} L_j + \sum_{j=10}^{11} L_j = L_3^* \tag{16}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{6} L_j + \sum_{j=12}^{14} L_j = L_4^* \tag{17}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{6} L_j + \sum_{j=12}^{12} L_j + \sum_{j=15}^{16} L_j = L_5^* \tag{18}$$

For Iran Entrance Point:

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{6} L_j + \sum_{j=7}^{8} L_j = L_1^* \tag{19}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{6} L_j + \sum_{j=9}^{11} L_j = L_2^* \tag{20}$$

$$\sum_{j=1}^{3} L_j + \sum_{j=6}^{6} L_j + \sum_{j=9}^{9} L_j + \sum_{j=12}^{13} L_j = L_3^* \tag{21}$$

$$\sum_{j=1}^{5} L_j = L_4^* \tag{22}$$

For Russia (Blue Stream) Entrance Point

$$\sum_{j=1}^{4} L_j = L_1^* \tag{23}$$

For Azerbaijan Entrance Point

$$\sum_{j=1}^{3} L_j = L_1^* \tag{24}$$

For Nigeria & Algeria Entrance Point

$$\sum_{j=1}^{3} L_j = L_1^* \tag{25}$$

Table 8. Lengths of the branches

Length (miles)	Entrance Points	Russia (west)	Iran	Russia (Blue Stream)	Azerbaijan	Nigeria & Algeria
L_1^*		359	822.5	301.3	118.6	13.6
L_2^*		504	886.5	---	---	---
L_3^*		410	1202	---	---	---
L_4^*		495	690	---	---	---
L_5^*		473.5	---	---	---	---

Second class of equality constraints about flow rate is also the same with the chapter 3.

5.5. Compressor Stations

In Turkish NG network, there are totally 8 compressors, which are being installed and now are in service. Four of them are on the first network part which is coming from the first entrance point Russia (westward), two of them are on the second part which is coming from Iran, one of them is on third part that is coming from Russia (Blue Stream) and last one is on fourth part, coming from Azerbaijan.

Table 9. Compressor stations and entrance points (Source: Botas)

Name and Location	Flow Capacity (Sm3/h)	Minimum inlet& outlet pressures (p_s)	Maximum inlet &outlet pressures (p_d)	Entrance Point
Kirklareli CS-1 Compressor Station	2,500,000	37	75	Russian Federation (westward)
Ambarli CS-2 Compressor Station	1,500,000	41	75	Russian Federation (westward)
Pendik CS-3 Compressor Station	1,400,000	40	75	Russian Federation (westward)
Eskisehir CS-5 Compressor Station	400,000	40	75	Russian Federation (westward)
D. Beyazit CS-11 Compressor Station	1,600,000	40	75	IRAN
Corum Compressor Station (new)	1350000	39	75	Russian Federation (Blue Stream)
Hanak Compressor Station (new)	1100000	40	70	AZERBAIJAN
Sivas Compressor Station (new)	1200000	37	70	IRAN

In our model, we give the first initial values to flow rate variable according to table 8 above. For example, the starting flow rate of Russia (west) is the same with the CS-1 compressor station`s flow rate, because Kirklareli is located on this entrance point and the firs state in this line.

5.6. Main Transmission Lines and Its Current Diameter and Lengths

The total length of transmission lines (see Figure 15) that we are optimizing is currently 9,555 km (5937 miles).

Figure 15. Transmission Line (Source: Botas)

Diameter and Length

These information and data that are reflected on the tables below are used to determine the simple bounds and initial points for diameters and lengths as explained below.

Malkoçlar-Ankara Natural Gas Main Transmission Line (Russia West Entrance Point):

Table 10. Entrance Point: Bulgaria-Turkey Boundary (Malkoclar)

Point	Pipeline	Diameter (D_j) (inches)	Line Length (L_j))(km)
A	Malkoçlar-Ambarlı	36	220.659
	Marmara Dnz.Geçişi Ambarlı-Pendik	2x30	106.268
	Pendik-Demirciler	36	33.200
	Demirciler-Muallimköy	24	7.234
D	Muallimköy-Hersek(Dnz.Geçişi)	2x24	12.850
	Hersek-Yumurtatepe (Bursa)	24	48.266
E	Yumurtatepe (Bursa)-Seçköy	24	11.918
	Seçköy-Yapracık	24	351.691
y	Yapracık-Güvercinlik	30	18.828

Table 11. Demirciler(Gebze) - Blacksea Eregli Natural Gas Main Transmission Line:

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
D	Demirciler(Gebze)-Pazarcık	24	18.089
	Pazarcık-Adapazarı	24	66.611
	Adapazarı-Düzce	18	64.890
C	Düzce-Ereğli	16	62.099

Table 12. Seckoy(Bursa) – Canakkale Natural Gas Main Transmission Line:

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
E	Seçköy-Karacabey	24	73.700
	Karacabey-Bandırma	16	30.863
	Bandırma-Çan Pig İstasyonu	12	10.637
F	Çan Pig İstasyonu-Çanakkale	12	106.500

Table 13. Karacabey-Bornova (Izmir) Natural Gas Main Transmission Line:

	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
G	Karacabey-Üçpınar Pig (Manisa)	36	212.555
	Üçpınar Pig -Bornova	36	28.645
H	Üçpınar Pig –Aliağa Pig	36	36.000

Table 14. Bozuyuk-Usak Natural Gas Main Transmission Line:

	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
I	Bozuyük-Kütahya	20	62.108
J	Kütahya-Uşak RM/A Pig İstasyonu	16	115.585

To calculate the length of the entrance points we assigned a letter in the map (see Appendix B) such as A, B, C, a, b, c, x, y etc. to transmission lines which are shown in the tables above. According to these letters we can calculate the length bounds.

- By considering main exit points from Russian Federation (westward), which has five exit points, we can use equations below.

- 1st entrance & exit point and 1st branch:

    Malkoclar-Eregli [(A-D)+(D-C)] ➜ (367.127km)+(211.689km)=

578.816km=359 miles = L_1^*

- 2nd entrance & exit point and also 2nd branch:

    Malkoclar-Yapracik/ Ankara (A-y) ➜ 810.914km = 504 miles= L_2^*

- 3rd entrance & exit point and 3rd branch:

    Malkoclar-Usak [(A-D)+(D-E)+(E-I)+(I-

J)]➜(367.127km)+(80.268km)+(60.184)+(177.693km)= 685.272km =410

miles= L_3^*

- 4th entrance & exit point and 4th branch:

    Malkoclar-Izmir [(A-D)+(D-E)+(E-G)+(G-

H)]➜(367.127km)+(80.268km)+(73.700km)+(277.200km)= 798.295km=495

miles = L_4^*

- 5th entrance & exit point and 5th branch:

    Malkoclar-Canakkale [(A-D)+(D-E)+(E-F)] ➜

(367.127km)+(80.268km)+(314.700km)= 762.950km= 473,5 miles = L_5^*

Table 15. Konya-Izmir Natural Gas Main Transmission Line:

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
S	Konya-Isparta	40	217.400
	Isparta-Nazilli	40	202.800
T	Nazilli-İzmir	40	198.300

Table 16. Sivas-Mersin Natural Gas Main Transmission Line:

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
K	Sivas-Malatya	40	167.375
	Malatya-Gaziantep	40	181.500
L	Gaziantep-Mersin	40	215.125

East Anatolia Natural Gas Main Transmission Line:

Table 17. Entrance Point: Iran-Turkey Boundary (Gurbulak)

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
a-c	Doğu Beyazıt-Kayseri	48	851.138
c-y	Kayseri-Ahiboz (Gölbaşı-Ankara)	40	259.147
c-s	Kayseri-Konya	40	205.158
c-b	Konya-Seydişehir	16	111.684

- By considering main exit points from Iran, which has four exit points, we can use equations below.
- 1st entrance & exit point and also 1st branch:

    Dogu Beyazit - Mersin [(a-K)+(K-L)]➔

    (760.138km)+(564km)=1324.138km=822,5 miles = L_1^*
- 2nd entrance & exit point and 2nd branch:

    Dogu Beyazit - Seydisehir [(a-c)+(c-b)] ➔ (1110.285km)+(316.842km)

    = 1427.127km=886,5 miles = L_2^*
- 3rd entrance & exit point and 3rd branch:

    Dogu Beyazit - Izmir [(a-C)+(C-S)+(S-T)➔

    (1110.285km)+(205.158km)+(618.500km)= 1933.943km=1202 miles = L_3^*
- 4th entrance & exit point and 4th branch:

    Dogu Beyazit - Ankara (a-Y)➔ 1110.285km = 690 miles = L_4^*

Blue Stream Natural Gas Main Transmission Line:

- By considering main exit points from Russia (Blue Stream), which has one exit point, we can use equations below.
- 1st entrance & exit point and 1st branch:

    Samsun - Yapracik/Ankara (X-Y)➔ 501km= 301.3 miles = L_1^*

Table 18. Entrance Point: Black Sea (Samsun)

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
x-y	Samsun-Ankara (Temelli)	48	501.0

Marmara Ereglisi LNG Terminal Main Line Connection:
- • By considering main exit points from Nigeria & Algeria, which has one exit point, we can use equations below.
- - 1st entrance & exit point and 1st branch:

    LNG Terminal - Corlu/Tekirdag (m-n)➔ 22.513km = 13,6 miles=L_1^*

Table 19. Entrance Point (Nigeria & Algeria): Marmara Ereglisi (Tekirdag)

Point	Pipeline	Diameter (D_j) (inches)	Line Lenghth (L_j))(km)
m-n	LNG Terminal-Ana Hat Çorlu	24	22.513

- • By considering main exit points from Azerbaijan, which has one exit point, we can use equations below.
- - 1st entrance & exit point and 1st branch:

    Ardahan - Erzurum ➔191km= 118.6 miles = L_1^*

From the above tables, we can determine the bounds and constraints for Turkish natural gas network system according to these values that are reflected above.

For example, in Russia (west) network, there are five branches and there should be five diameter bounds for them. Malkoclar is located on the first branch in this network and its diameter is 36 inches. It is the highest value among the cities, which are located in Russia (west) pipeline network. All of the lower bounds of diameters are bounded according to definition of diameters in introduction part and the lower bounds for all branches are 6 inches. So, our upper bound of branch one for diameter is 36

inches. Diameter bounds for the other four branches in Russia (west) network will be as following:

- 1st branch: between the points A and C and according to table 9 and table 10, upper bound should be 36 inches. ($D_1^{max} = 36$)

- 2nd branch: between points A and B and according to table 9, upper bound should be 36 inches. (D_2^{max})= 36)

- 3rd branch: between points A and J and according to tables between 9 and 13, upper bound should be 24 inches. (D_3^{max}= 24)

- 4th branch: between points A and H and according to tables between 9 and 12, upper bound should be 36 inches. (D_4^{max}= 36)

- 5th branch: between points A and F and according to tables between 9 and 11, upper bound should be 36 inches. (D_5^{max}= 36)

Doing the same method mentioned above also bound other four entrance points and its network. These four diameter bounds for the four different networks are shown above:

Iran (4 branches):

- 1st branch: between the points a and L and according to table 15 and table 16, upper bound should be 40 inches. (D_1^{max}= 40)

- 2nd branch: between points a and b and according to table 16, upper bound should be 40 inches. (D_2^{max}= 40)

- 3rd branch: between points a and T and according to table 14 and 16, upper bound should be 40 inches. (D_3^{max}= 40)

- 4th branch: between points a and y and according to table 16 and 17, upper bound should be 48 inches. (D_4^{max}= 48)

- Lower bound will be 16 inches for all the branches according to tables between 14 and 17. (D_i^{min}= 16)

Russia (Blue Stream) (1 branch):

- 1st branch: between the points x and y and according to table 17, upper and lower bounds should be the same as 48 inches. ($\boldsymbol{D_1^{min} = D_1^{max}} = 48$)

Azerbaijan (1 branch):

- 1st branch: between the points Erzurum and Ardahan, upper bound should be the 36 inches. ($\boldsymbol{D_1^{max}} = 36$)

- Lower bound will be 24 inches for this branch. ($\boldsymbol{D_1^{min}} = 24$)

Nigeria&Algeria (1 branch):

- 1st branch: between points m and n and according to table 18, upper and lower bounds should be the same as 24 inches. ($\boldsymbol{D_1^{min} = D_1^{max}} = 24$)

5.7. Main Entrance Points

There are totally five main entrance points and natural gas network are arranged by using these entrance points and its lengths.

1. Russia Westward- Turkey Main Transmission Line

This line is entering Turkey from Malkoclar from the border of Bulgaria. Then the followed line is through Ambarli, Hamitabat, Izmit, Istanbul, Eskisehir and Bursa who routes with the 845 kilometers long (545 miles) pipelines (BOTAS, 2011). The final point is Ankara.

In this Entrance point, four compressor stations that are Kirklareli, Ambarli, Pendik and Eskisehir, exist and maximum operation pressures of the pipelines is 75 psi (EMRA, 2011).

2. Iran Main Transmission Line

It starts from Dogubeyazit and goes approximately 1.491 km-long lines and then finally reaches to last point of Yapracik/Ankara via Erzurum, Sivas, and Kayseri with another branch from Seydisehir via Kayseri and Konya (Botas, 2011).

3. Russia Blue Stream Transmission Line (Blue Stream)

The starting point of this line is Samsun and it goes to main network center of Ankara via cities of Kirikkale, Corum and Amasya (Botas, 2011).

4. Azerbaijan – Turkey Natural Gas Pipeline (Shahdeniz)

This line and project are very important for Turkey for the energy-related topics. After the construction Baku-Tbilisi-Ceyhan COP has been finished with its parallel line named Shahdeniz, Turkey`s role will be more effective in the world and Europe (Botas, 2011).

5. Nigeria & Algeria LNG Pipeline

This natural gas pipeline is especially responsible for the LNG import and export activities and also for supplying LNG to Turkey.

5.8. Basic Design Conditions for Model 2

We used almost the same parameters with Edgar et al. (1978) model parameters to define basic design conditions for the model of Tabkhi et al. (2009). Also, we used the related data from table 6 above for this optimization problem. The design parameters and conditions are shown below in detail.

Pipeline design temperature   : 323.15 K
Average molecular mass of gas   : 20 (g per mol)
Design factor   : 0.4
Seam joint factor   : 0.8
Temperature factor   : 1
Universal gas constant   : 8314 J per kmol K
Compressibility factor   : 0.90
Isentropic exponent   : 1.32
Compressor isentropic efficiency   : 0.75

Mechanical efficiency	: 0.90	
Driver efficiency	: 0.35	
Low heating value	: 47.141	
Pipe unit capital cost (euro per km m year)		: 9570
Compressor fixed unit capital cost (euro per year)		: 33910
Variable unit capital cost (euro per kwatt)		: 523
Operating cos t(euro per kw year)		: 70

For used steel, SMYS (specified minimum yield strength), which is necessary to determine pipeline maximum allowable operating pressure (MAOP), is assumed to be equal to 2000 bars. Design factor which is one of another parameter to calculate MAOP, considered 0.4 that is low enough and safe value (Tabkhi et al. 2009).

CHAPTER 6

COMPUTATIONAL RESULTS

6.1. Results for Model 1

We applied the proposed solution technique to the Turkish natural gas pipeline network system to get the optimal design of its network with the optimal diameter, length, suction and discharge pressures and solved this problem by considering with compressor`s total horsepower in whole network. An adequate solver, namely CONOPT, within GAMS (General Algebraic Modeling System) environment was selected to implement nonlinear programming algorithm with branch and bound technique. The original model which is modeled by Edgar et al. (1978) with using GAMS solver are used with re-arranged version according to Turkish natural gas network system (see Appendix C).

There are totally five main entrance points in a whole network of Turkish natural gas pipeline system. So, we have applied our model to all of the entrance points and their whole networks.

Figures 16 to 20 and Tables 20 to 24 show the solution to this case of Turkish natural gas pipeline network system. Compressor stations are assigned to all networks according to connection points to make the natural gas supply easy to distribute to all points in the network. Red colors represent the current compressor stations, while extra compressors that are assigned according to connection points for the projection of future, are represented by blue color compressor stations.

There are five different branches exist in the entrance point of Russia (westward) and the maximum number of compressors in all branches were set to 11. Secondly, there are four different branches exist in the entrance point of Iran and the maximum number of compressors in all branches were set to 9. Third there are only one branch exists in the

entrance point of Russia (Blue Stream) and the maximum number of compressors in all branches were set at 3. Lastly, in the entrance point of Azerbaijan and Nigeria & Algeria entrance points, there are one branches of each and the maximum number of compressors in each network was set to 2.

The initial configuration of entrance points and their networks have two colors to show the current and extra compressor stations. Blue color represents the extra compressor in the network while red color shows the current constructed compressor stations. To get the current network design we can remove the blue compressor stations from the network then we can get the corresponding sub network before optimization.

The following constraints and information are given to explain the specificities of the entrance point of **Russia (westward)** and its pipeline network system. Fixed input pressure is 82 psi with a flow rate of 2500000 sm^3/h, and five different output pressures in pipeline segments 5,9,11,14,16 were set at 40 psi, 37 psi, 41 psi, 39 psi, 41 psi, respectively on the pipeline network of Russia (westward).

Figure 16.a. Russian Federation initial configuration (westward) (entrance and exit points)

The total length of five different branches constrained to be 579 miles, 504 miles, 510 miles, 474 miles and 495 miles, in sequence. On each pipeline segment, 5 miles is placed as a lower bound. In Russia-West network CS1, CS2, CS3 and CS4 that have red color in figure 16.a, are currently in process while CS5 to CS11 are assigned as extra compressor stations for this network.

Figure 16.b. Optimal configuration of Russian Federation (westward) with optimal pipeline lengths (in mile) shown on arcs

After optimization of this system, we got only one compressor that is enough for this part to supply and arrange the pressure points with the optimal diameters and flow rates. Also, we obtained one compressor work and our first 3 lengths are the same and we can put our new compressor whichever these 3 points we want. See Figure 16 a&b.

Table 20. Optimal values related to operating variables for (Russia- West)

Pipeline Segment	Discharge (p_d) (psi)	Suction (p_s) (psi)	Pipe diameter (D_j) (in.)	Length (L_j) (mile)	Flow rate (Q_j) (sm^3/h)
S1	90.00	82.00	12.901	140.000	2500000.000
S2	82.000	70.335	12.274	140.000	2487500.000
S3	70.335	56.302	12.274	140.000	2487500.000
S4	56.302	40.000	6.228	128.343	400000.000
S5	40.000	35.000	6.228	30.657	400000.000
S6	56.302	47.862	10.320	39.000	2087500.000
S7	47.862	41.488	7.955	28.709	978257.158
S8	41.488	37.000	6.000	11.291	578257.158
S9	37.000	35.000	6.090	5.000	578257.158
S10	41.488	41.000	6.737	5.000	400000.000
S11	41.000	37.721	6.000	17.291	400000.000
S12	47.862	41.900	6.079	5.000	1109242.842
S13	41.900	39.000	6.000	5.000	709242.842
S14	39.000	35.866	6.000	5.000	709242.842
S15	41.900	41.000	6.000	5.000	400000.000
S16	41.000	35.957	6.000	26.000	400000.000

Compressor Station	Compression Ratio	Capital Cost ($/year)
C1	1.000	44450

The second following constraints and information are given to explain the specificities of the entrance point of **Iran** and its pipeline network system. Fixed input pressure is 50 psi with a flow rate of 2500000 sm^3/h, and four different output pressures in pipeline segments 5,8,11,13 were set at 40 psi, 40 psi, 36 psi, 37 psi, respectively on the pipeline network of Iran.
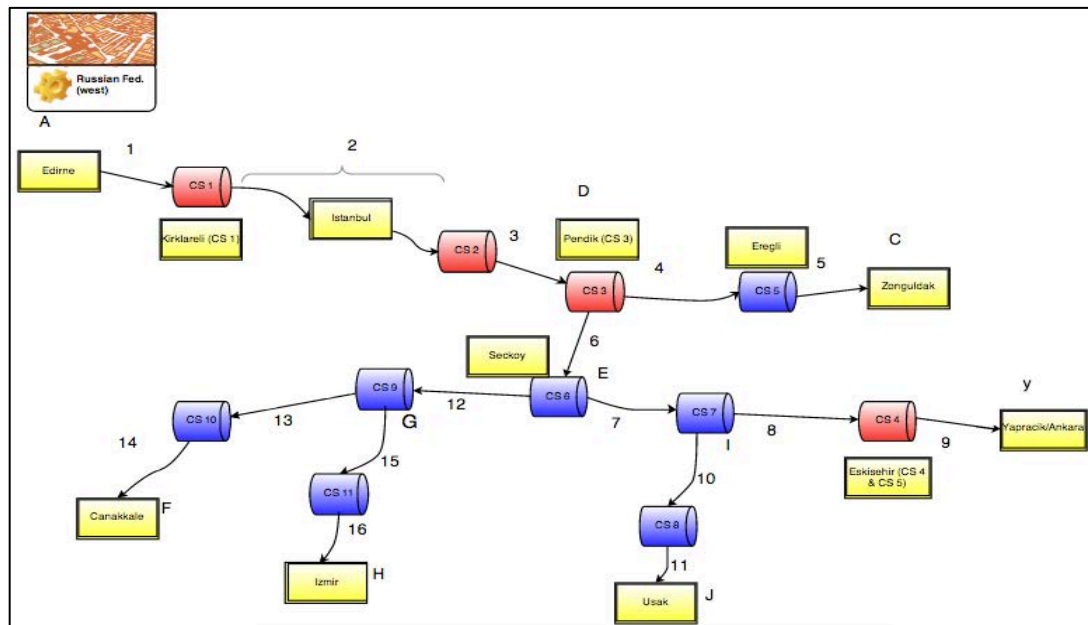
The total length of four different branches on network of Iran entrance points constrained to be 690 miles, 1202 miles, 887 miles, and 823 miles, in sequence. On each pipeline segment, 70 miles is placed as a lower bound. See Figure 17.

Figure 17. a&b. Initial and final optimal gas transmission system (Iran)

In Iran network CS1and CS2 that have red color in figure 17, are currently in process while CS3 to CS9 are assigned as extra compressor stations for this network.
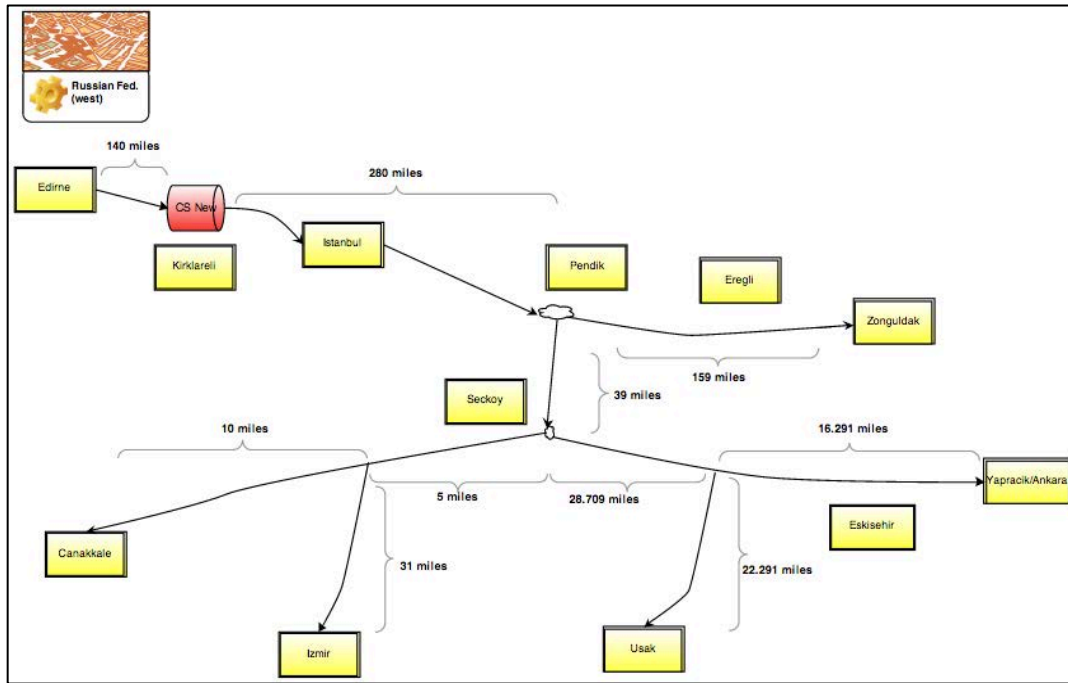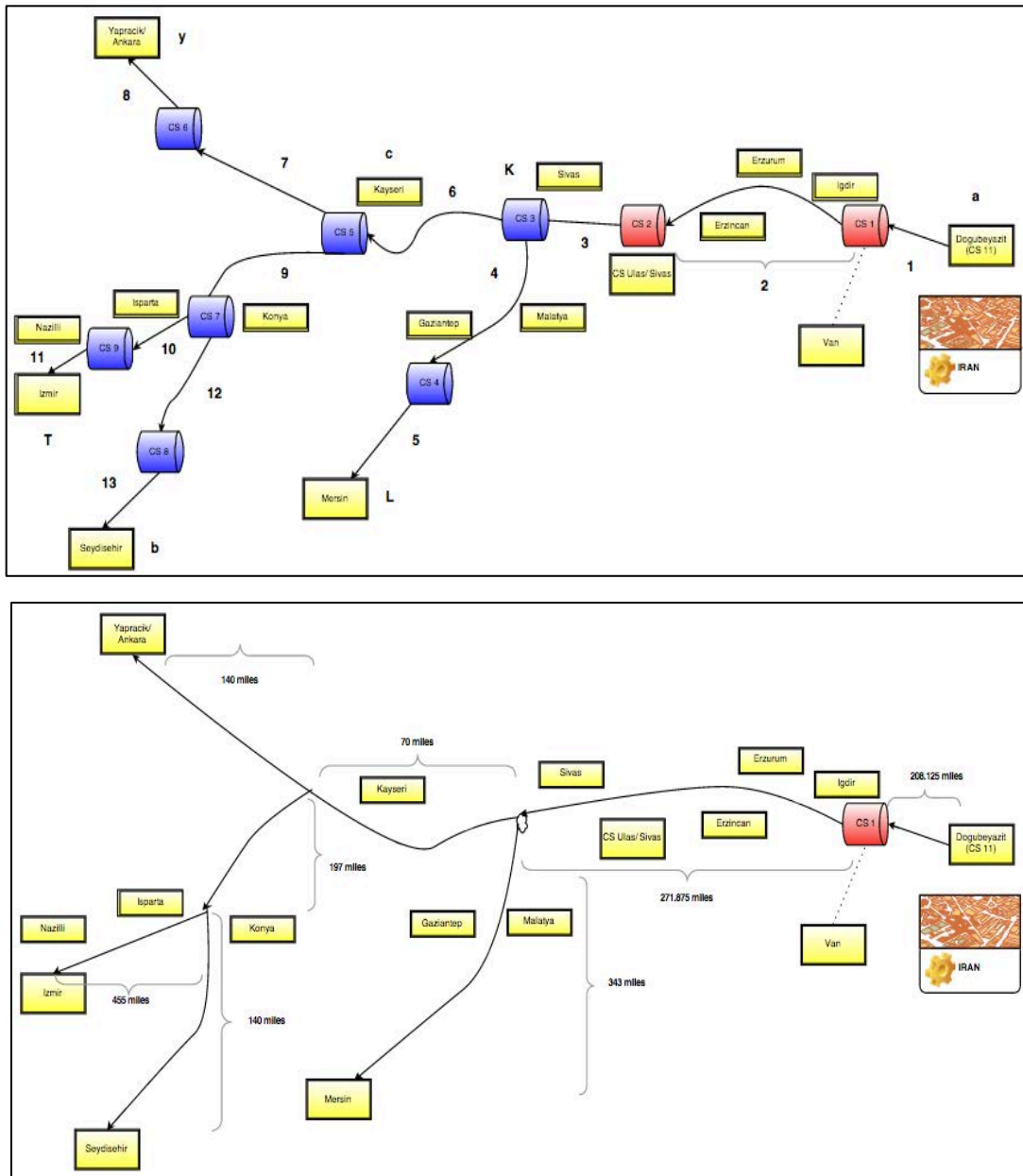
Table 21. Optimal values related to operating variables for Iran

Pipeline Segment	Discharge (p_d) (psi)	Suction (p_s) (psi)	Pipe diameter (D_j) (in.)	Length (L_j) (mile)	Flow rate (Q_j) (sm^3/h)
S1	56.115	50.000	16.000	208.125	2500000.000
S2	50.000	44.923	16.000	154.568	2500000.000
S3	44.923	40.649	16.000	117.307	2500000.000
S4	40.649	40.000	16.000	273.000	619715.866
S5	40.000	39.832	16.000	70.000	619715.866
S6	40.649	40.070	19.198	70.000	1880284.134
S7	40.070	40.000	16.000	70.000	400000.000
S8	40.000	39.930	16.000	70.000	400000.000
S9	40.070	37.286	16.000	197.000	1480284.134
S10	37.286	36.000	16.000	385.000	700460.697
S11	36.000	35.761	16.000	70.000	700460.697
S12	37.286	37.000	16.000	70.000	779823.436
S13	37.000	39.000	16.000	70.000	779823.436

Compressor Station	Compression Ratio	Capital Cost ($/year)
C1	1.000	44450

The third following constraints and information are given to explain the specificities of the entrance point of **Russia (Blue Stream)** and its pipeline network system. Fixed input pressure is 53 psi with a flow rate of 1350000 sm^3/h, and output pressure was set at 53 psi. The total length of branch constrained to be 302 miles. We placed a lower bound of 60 miles on each pipeline segment in this network. See Figure 18.

In Russia-Blue Stream network CS2 that has red color in figure 18, is currently in process while CS1 and CS3 are assigned as extra compressor (blue color) stations for this network.

Figure 18. Initial and final optimal gas transmission system of Russian Federation (Blue Stream)

Table 22. Optimal values related to operating variables for Russia (Blue Stream)

Pipeline Segment	Discharge (p_d) (psi)	Suction (p_s) (psi)	Pipe diameter (D_j) (in.)	Length (L_j) (mile)	Flow rate (Q_j) (sm^3/h)
S1	53.000	52.999	48.000	60.000	1350000.000
S2	52.999	52.997	48.000	60.000	1343250.000
S3	52.997	52.996	48.000	60.000	1336533.750
S4	53.003	53.000	48.000	122.000	1329851.081

Compressor Station	Compression Ratio	Capital Cost ($/year)
C1	1.000	44450
C2	1.000	44450
C3	1.000	44450

The fourth following constraints and information are given to explain the specificities of the entrance point of **Azerbaijan** and its pipeline network system.

In Azerbaijan network CS1 that has red color in figure 19, is currently in process while CS2 is assigned as extra compressor (blue color) stations for this network.
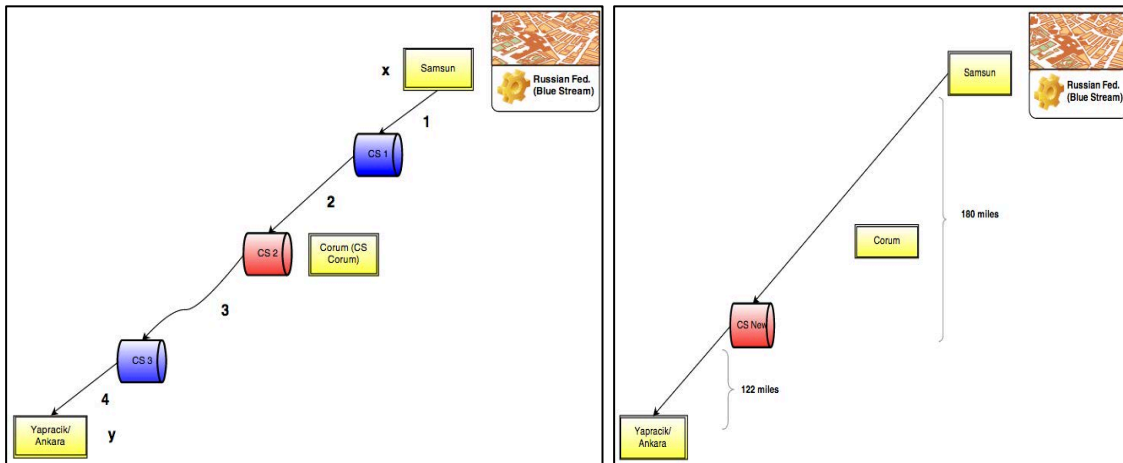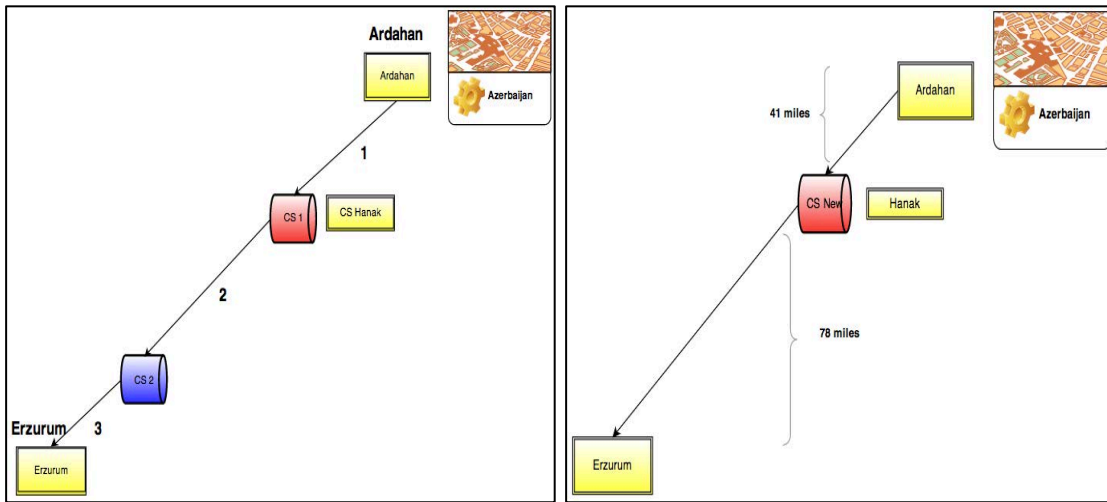
Figure 19. Initial and final optimal gas transmission system of Azerbaijan

Fixed input pressure is 55 psi with a flow rate of 1100000 sm^3/h, and output pressure was set at 55 psi. The total length of branch constrained to be 119 miles. We have 3 compressor stations, which can be assigned as optimal each, but one of them, which is third one, has the highest rate of work with 8134.584 according to equation (1). So, it is the best way to place new compressor to this point on the network because of work of the compressor to get the more optimal result. On each pipeline segment, 39 miles is placed as a lower bound. See Figure 19.

Table 23. Optimal values related to operating variables for Azerbaijan

Pipeline Segment	Discharge (p_d) (psi)	Suction (p_s) (psi)	Pipe diameter (D_j) $(in.)$	Length (L_j) $(mile)$	Flow rate (Q_j) (sm^3/h)
S1	55.026	55.000	24.000	41.000	1100000.000
S2	55.007	55.003	34.540	39.000	1094500.000
S3	55.003	55.000	34.540	39.000	1094500.000

Compressor Station	Compression Ratio	Capital Cost ($/year)
C1	1.000	44450

Lastly, the fifth following constraints and information are given to explain the specificities of the entrance point of **Nigeria & Algeria** and its pipeline network system. In this network there is no compressor stations currently being used while CS1 and CS2 are assigned as extra compressor (blue color) stations for this network.
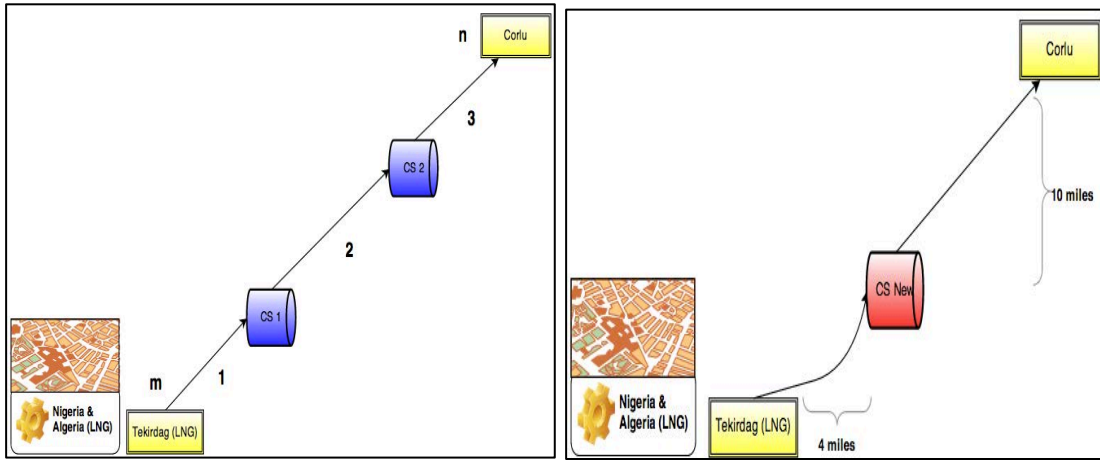
Figure 20. Initial and final optimal gas transmission system (Nigeria &Algeria)

We have one compressor station, which can be assigned as optimal, has the work of 6214.486 according to equation (1). So, it is the better way to place new compressor to this point (point one, see figure 20) on the network because of this work of compressor.

Table 24. Optimal values related to operating variables for Nigeria & Algeria

Pipeline Segment	Discharge (p_d) (psi)	Suction (p_s) (psi)	Pipe diameter (D_j) $(in.)$	Length (L_j) $(mile)$	Flow rate (Q_j) (sm^3/h)
S1	52.000	51.998	24.000	2.000	1500000.000
S2	51.998	51.995	24.000	2.000	1492500.000
S3	52.012	52.000	24.000	10.000	1485037.500

Compressor Station	Compression Ratio	Capital Cost ($/year)
C1	1.000	44450
C2	1.000	44450

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Fixed input pressure is 52 psi with a flow rate of 1500000 sm^3/h, and output pressure was set at 52 psi. The total length of branch constrained to be 14 miles. 2 miles was assigned on each pipeline segment as lower bound. See Figure 20. We have two compressor stations, which can be assigned as optimal. But, one of them, which is first one, has the highest rate of work with 21821.901 according to equation (1). So, it is the appropriate way to place new compressor to second point (see figure 20) on the network because of this work of compressor to get the more optimal result.

The problems that we mentioned and considered for Turkish natural gas pipeline network system above, are solved by using the nonlinear optimization algorithm with the branch and bound technique. After the solution procedure, the obtained optimal network with the optimal variables are shown in Appendix C.

6.2. Results of Model 2

According to the study of " Total Cost Minimization of a High-Pressure Natural Gas Network", made by Tabkhi et al. (2009), we selected GAMS environment to solve our mixed integer linear programming (MINLP) problem. The solvers of CONOPT and DICOPT are chosen as solution method for this model.

We applied this optimization technique to the same network from Turkish natural gas pipeline system to compare the results with Edgar et al. (2009) optimization model. We still have five different entrance points. Current compressor stations are assigned to optimization problem to figure out and check whether they are enough or extra for current system according to diameter size, pipe length, operation cost, maintenance cost, compressor cost, flow rate and pressures. Also in this model length of the pipeline segments are fixed. Current map of natural gas pipeline system with current compressor stations are shown in section 6.1. We will give the results for new model in this section with the optimal natural gas networks.

According to Tabkhi et al. (2009) optimization technique, we did some changes on the pipeline segments. Because in this model, we should consider the cities` gas demands to get the appropriate value for flow rates. So, we now have 19 pipeline segments in this model for Russia west network. Also we assigned the current four compressor stations to check the optimality of this network. Results for Russia west network are shown in table 25.
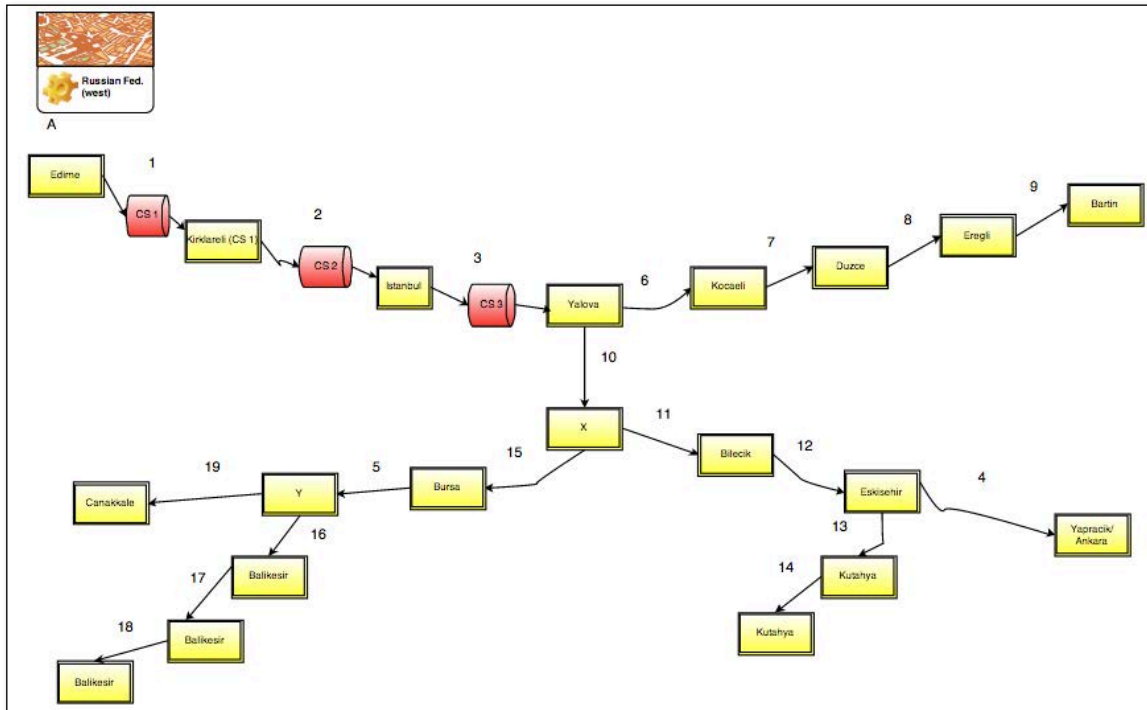
Figure 21. Optimal design of Russia West Entrance Point (model 2)

Table 25. Results for Russia West Network

Results (Russia West)					
Pipeline segment	Pressure (MAOP) (bar) $p \leq$ MAOP	Length (miles)	Diameter (inches)	Flow Rate (sm3/h)	Wall Tickness (m)
1	70.641	111.2	12.9	1022544	0.017
2	70.663	138.6	12.28	1028682	0.016
3	70.663	82.02	12.28	1261645.2	0.016
4	70.558	57.16	15.98	508212	0.021

Table. 25 continued

Pipeline segment	Pressure (MAOP) (bar) $p \leq$ MAOP	Length (miles)	Diameter (inches)	Flow Rate (sm3/h)	Wall Tickness (m)
	Results (Russia West)				
5	70.442	24.85	24	418885.2	0.032
6	71.102	42.87	6.22	5241.6	0.008
7	71.163	80.16	5.83	153493.2	0.008
8	71.234	63.38	5.43	19274.4	0.007
9	71.316	60.89	5.03	1346.4	0.007
10	70.442	30.45	24	978170.4	0.032
11	70.673	39.15	12	595789.2	0.016
12	70.442	37.28	24	588063.6	0.032
13	70.365	32.31	36	51073.2	0.048
14	70.365	39.15	36	28537.2	0.048
15	70.442	17.40	24	486946.8	0.032
16	70.673	19.88	12	439214.4	0.016
17	70.673	32.31	12	342025.2	0.016
18	70.673	17.39	12	322758	0.016
19	70.673	90.09	12	35024.4	0.016

Pipeline segment	Power (hp)	Mass flow rate of compressed gas (kg/s)	Compressor isentropic head (m)	Velocity
	Compressor Station Related Results			
1	31161.44	14.9676	3358.6634	240.31
2	37131.77	14.9676	5088.7132	220.14
3	45567.5	14.9676	6938.332	198.72

Node		Node	
	Gas delivery or supply (kg/s)		
1	11.574	11	22.852
2	9.867	12	143.519
3	400.752	13	16.591

Table. 25 continued

Gas delivery or supply (kg/s)			
Node		**Node**	
4	6.128	**14**	9.902
5	47.309	**15**	77.778
6	10.026	**16**	6.597
7	5.046	**17**	33.594
8	5.451	**18**	38.946
9	4.832	**19**	115.741
10	5.906	**20**	14.285

After optimization of this network, three of four compressor stations are obtained as optimal for current system. Figure 21 shows the optimal design of this network.

We have 13 pipeline arc segments including compressor arcs in this model for Iran network. We assigned the current two compressor stations to check the optimality of this network. Results for Iran network are shown in table 26.
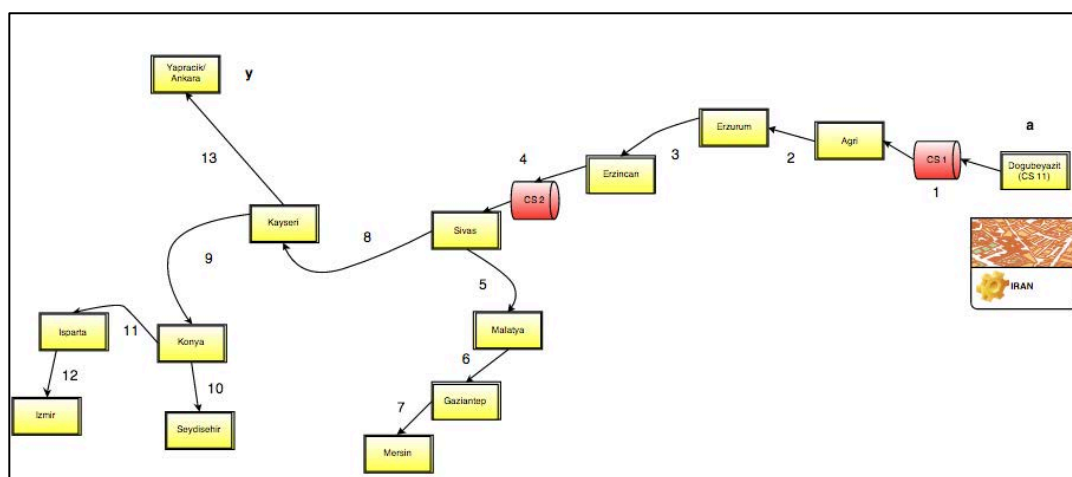
Figure 22. Optimal design of Iran Entrance Point (model 2)

After optimization of this network, two compressor stations are obtained as optimal for current system. Figure 22 shows the optimal design of this network.

Table 26. Results for Iran Entrance Network

	Results (Iran)				
Pipeline segment	**Pressure (MAOP) (bar) $p \leq$ MAOP**	**Length (miles)**	**Diameter (inches)**	**Flow Rate (sm3/h)**	**Wall Tickness (m)**
1	70.327	74.56	47.99	1242115.2	0.063
2	70.327	119.93	47.99	1151906.4	0.063
3	70.327	117.44	47.99	1104818.4	0.063
4	70.327	160.31	47.99	1221487.2	0.063
5	70.350	103.77	40	135360	0.053
6	70.350	113.09	40	120981.6	0.053
7	70.350	133.60	40	37231.2	0.053
8	70.327	155.34	47.99	1001548.8	0.063
9	70.350	158.45	40	463039.2	0.053
10	70.350	100.66	40	202618.8	0.053
11	70.350	165.91	40	260420.4	0.053
12	70.350	249.8	40	425314.8	0.053
13	70.327	62.14	47.99	470696.4	0.063

	Compressor Station Related Results			
Pipeline segment	**Power (hp)**	**Mass flow rate of compressed gas (kg/s)**	**Compressor isentropic head (m)**	**Velocity**
1	42096.46	22.82	1796.2315	206.75
2	52464.516	22.82	2239.9785	185.20

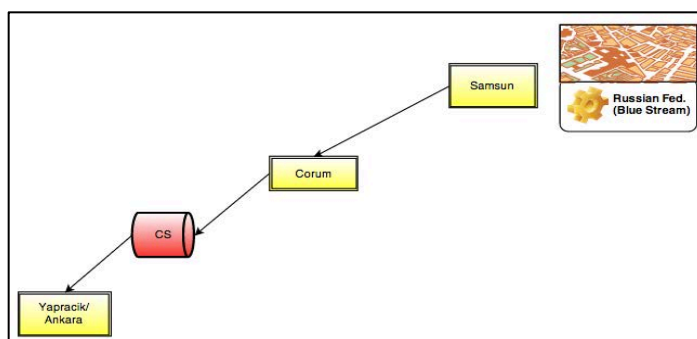| *Gas delivery or supply (kg/s)*			
Node		**Node**	
1	3.443	8	48.698
2	15.972	9	36.892
3	22.512	10	57.870
4	6.308	11	1.852
5	18.055	12	12.066
6	22.049	13	115.741
7	52.083	14	143.692

Figure 23. Optimal design of Blue Stream Entrance Point (model 2)

We have 2 pipeline arc segments including compressor arcs and three nodes (cities) in this model for Russia-Blue Stream network. We assigned one compressor station to check the optimality of this network. Results for Blue Stream network are shown in table 27.

Table 27. Results for Russia Blue Stream Entrance Point

			Results (Russia Blue Stream)		
Pipeline segment	**Pressure (MAOP) (bar) $p \leq$ MAOP**	**Length (miles)**	**Diameter (inches)**	**Flow Rate (sm3/h)**	**Wall Tickness (m)**
1	70.327	180.2	47.99	635418	0.063
2	70.327	121.8	47.99	709696.8	0.063

	Compressor Station Related Results			
Pipeline segment	**Power (hp)**	**Mass flow rate of compressed gas (kg/s)**	**Compressor isentropic head (m)**	**Velocity**
1	43173.784	141.782	228.381	204.16

Gas delivery or supply (kg/s)	
Node	
1	36.168
2	15.535
3	141.782

After optimization of this network, one compressor station is obtained as optimal for current system. Figure 23 shows the optimal design of this network.

We have one pipeline segment including compressor arc and two nodes (cities) in this model for Azerbaijan entrance point network. We assigned one compressor station to check the optimality of this network. Results for Azerbaijan network are shown in table 28.
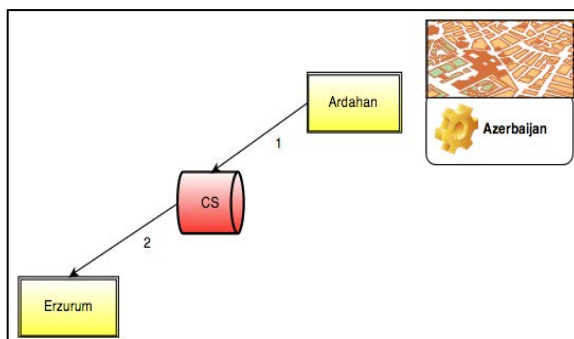

Figure 24. Optimal design of Azerbaijan Entrance Point (model 2)

Table 28. Results for Azerbaijan Entrance Point

Results (Azerbaijan)					
Pipeline segment	**Pressure (MAOP) (bar) $p \leq$MAOP**	**Length (miles)**	**Diameter (inches)**	**Flow Rate (sm3/h)**	**Wall Tickness (m)**
1	70.442	118.99	24.02	81039.6	0.032

	Compressor Station Related Results			
Pipeline segment	**Power (hp)**	**Mass flow rate of compressed gas (kg/s)**	**Compressor isentropic head (m)**	**Velocity**
1	18829.885	6.192	2280.752	309.14

Gas delivery or supply (kg/s)	
Node	
1	22.511
2	3.096

After optimization of this network, one compressor station is obtained as optimal for current system. Figure 24 shows the optimal design of this network.

We have one pipeline segment including compressor arc and two nodes (cities) in this model for Nigeria &Algeria entrance point network. We assigned one compressor station to check the optimality of this network. Results for Nigeria &Algeria network are shown in table 29.
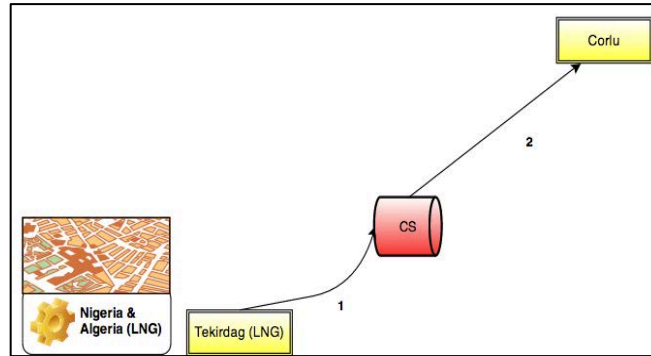

Figure 25. Optimal design of Nigeria & Algeria Entrance Point (model 2)

Table 29. Results for Nigeria &Algeria Entrance Point

Results (Nigeria &Algeria)					
Pipeline segment	Pressure (MAOP) (bar) $p \leq$ MAOP	Length (miles)	Diameter (inches)	Flow Rate (sm3/h)	Wall Tickness (m)
1	70.442	14	24	28648.8	0.032

	Compressor Station Related Results			
Pipeline segment	Power (hp)	Mass flow rate of compressed gas (kg/s)	Compressor isentropic head (m)	Velocity
1	1835.140	49.336	27.898	990.24

Gas delivery or supply (kg/s)	
Node	
1	7.958
2	24.668

After optimization of this network, one compressor station is obtained as optimal for current system. Figure 25 shows the optimal design of this network.

Finally, after the solution procedure for model 2, the obtained optimal network with the optimal design parameters is shown in Appendix D.

CHAPTER 7
COMPARISON OF TWO MODELS

After the optimization of the first model (from Edgar et al. 1978), we found that the optimal gas transmission network with all the constraints with a single network were obtained for the case of Turkey as can be seen in section 6.1. Our objective function`s optimum value is obtained as 11,937,740 dollar /year by using this model while objective function`s first value was 20,485,390 dollars/year which is estimated based on BOTAS costs. It can be seen that this model helped us to save approximately $8.5 million. We also obtained five compressor stations as optimal for Turkey from the 32 possible compressor stations in the first state of our model. Appendix C reflects the final state of Turkish natural gas pipeline network according to first model results.

Also, after the optimization of the second model (from Tabkhi et al. 2009), we found the optimal gas transmission network with all the constraints with a single network for the case of Turkey, which can be seen in chapter 6.2. Our objective function`s optimum value is obtained as 18,733,680 dollar /year by using this model while objective function`s first value was 20,485,390 dollars/year which is estimated based on BOTAS costs. We also obtained eight compressor stations as optimal for Turkey. Appendix D reflects the final state of Turkish natural gas pipeline network according to second model results.

Table 30. Detailed costs of optimal and current designed networks & Comparison

Model 1 Costs of Networks	Model 2 Costs of Networks	Networks	Current Costs of Networks
$7,066,330	$7,038,900	Russia West	$14,237,346.05
$2,815,900	$7,212,100	Iran	$4,211,639.7
$400,790	$1,231,700	Azerbaijan	$614,561.7
$1,451,900	$3,130,600	Russia BS	$1,307,842.55
$202,820	$120,380	Nigeria & Algeria	$113,642
$11,937,740	$18,733,680	TOTAL	$20,485,390

Detailed cost of all entrance points with their pipeline segments are shown on table 30.

Comparison according to diameter sizes:

According to two models that we have done, second optimization model provides us more appropriate and efficient results comparing them to first model. Also it is close to current actual values of Turkish natural gas network system. It considers more realistic values for diameters to make the natural gas system optimal for the minimal operating costs.

Comparison according to pipeline lengths:

In first model we fixed the segments` length and the optimization procedure gave us an optimal pipeline segment lengths according to other dependent values, while the second model fixed the pipeline segment lengths according to real life and current lengths of pipeline segments.

Comparison according to pressure values:

We assigned compressor stations on all the pipeline segments to examine the optimal compressor station number and optimal place to put CSs. Comparing this method to second model, it seems first model could give more appropriate value to arrange the pressure values on the segments. In second model, we have maximum allowable operating pressure (MAOP) to set the pressures on the arcs. But it only gives the maximum value for the pressures while Edgar`s model is giving the exact value for pressures.

Comparison according to flow rates:

Second model is considering the demands for the cities namely nodes on natural gas pipeline network to arrange the flow rates, however first model is not considering these demand values for the optimality. So, second model gives more optimal and

accurate results to get the optimal flow rates according to optimization model from Tabkhi et al. (2009).

As a summary, model 2 has better results according to current system values and decision variables of lengths, diameter sizes, number of compressor stations and flow rates comparing them to model 1 results, even though pressure values of model 2 gave the small and general picture for future instead of giving detailed pressure values as in model 1 results.

CHAPTER 8

CONCLUSION

In the Turkish natural gas pipeline network system there are five entrance points and five different networks. Also, these networks have eight compressor stations that are still in process. After applying these optimization methods, we got 5 compressor stations from model 1 compared with 8 compressor stations in the current network. We can use these extra compressor stations from model 1 method for the new network systems in future. Also, we don`t have compressor station for the network of Nigeria & Algeria (LNG) at current network system; so we can move one of these extra compressor to this optimal network as shown in figure 27 according to model 1.

For the model 2, we got eight compressor stations for whole system. Currently there are 4 compressor stations in Russia-west network. But after optimization procedure we got three CSs for this entrance network. As we mentioned above, we don`t have CS in Nigeria & Algeria network. So, we also can use this extra compressor station for this network, because optimization model gives us a CS for this network. Even though we still have eight compressor stations for whole network, our total cost is less than current cost. As a result of this explanation, we can state that model 2 can also be used in future for new network systems and for now to analyze the current system for better and optimal progress.

Turkey, namely Turkish Petroleum Pipeline Corporation (BOTAS) is now working on some new agreements to supply natural gas to Turkey with the new countries that are rich and supply high quality natural gas. So, to save money and to decrease the operation, maintenance and capital cost of natural gas system, we can suggest the company to relocate these extra compressors on new networks instead of setting up the new compressors.

BOTAS was supplying gas to 62 cities in 2011 according to EMRA`s report (see figure 26). Now, the company supplies natural gas to 71 cities with their small towns and villages out of 81 cities in 2012 in Turkey. There are 10 cities left, including Agri, Igdir, Mugla, Artvin, Tunceli, Bingol, Mus, Bitlis, Mardin, and Sirnak. So, the results of this optimization about Turkish natural gas pipeline network give us a chance to suggest the company to invest money more in these new cities rather than investing in current expensive network. Because company can get more efficient natural gas transportation and distribution infrastructure by reducing the cost-related factors from current system. Then, they can design the new networks or re-design the small networks that are still under construction, according to these results and optimal information about their natural gas network system.
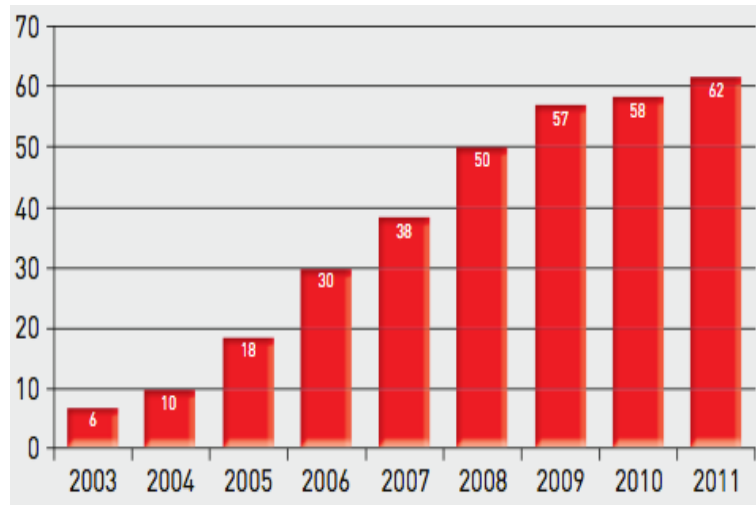

Figure 26. Number of cities provided with natural gas supply (Source: EMRA Sector Report, 2011)

Also, after getting the optimal variables such as suction and discharge pressures, diameters, lengths, flow rates, number of compressor stations and new segments, the company can supply enough natural gas as energy resource to meet customer demand in Turkey with decreased cost compared with the current system.

Moreover, according to these optimization results we can suggest that the new and optimal lengths, diameters and discharge and suction pressures can help the company to reduce and minimize the cost of operating compressors and pipelines. In model two, according to more realistic values of diameters and pipeline segment lengths, we can get more efficient information for current and future network design of natural gas system.

Table 31. Ongoing transmission and distribution lines in Turkey (Source: Botas, http://www.botas.gov.tr/index.asp)

Current Agreements	Supply (billion m^3/year)	Signature Date	Duration (year)	Completion Date
Algeria (LNG)	4	1988	20	2008
Nigeria (LNG)	1.2	1995	22	2017
Iran	10	1996	25	2021
Russian Fed. (Blue Stream)	16	1997	25	2022
Russian Fed. (West)	8	1998	23	2021
Turkmenistan	16	1999	30	2029
Azerbaijan	6.6	2001	15	2016

Table 31 shows the ongoing transmission and distribution lines in Turkey. Many of them are still in process and Turkish Petroleum Pipeline Corporation, the state company in Turkey for natural gas, is working on these networks. We applied our model to company`s current pipeline network. But after completion of these networks, the system will be more complex and it will be very hard to control and manage. So, to prevent this complexity, the company could use our optimization model to optimize their new networks. This information about the optimal design of the current natural gas pipeline

system can improve the future state of network system with the minimum cost and optimal values of the decision variables.

Furthermore, the studies to construct Erzincan Compressor Station and a natural gas underground storage facility at Tuz Golu (Salt Lake) Basin are proceeding and it is the most current project in Turkey for the natural gas supply. Internationally initiated transit pipelines and interconnection projects with neighboring countries are underway. So, company can relocate these extra compressors to these new networks and they can save money, time and effort after optimizing their network system. Also, optimal diameters, lengths, pressures at its optimal flow rates can give the idea to construct the new natural gas pipeline systems in Turkey.

In conclusion, we believed that these optimization techniques, which we have used to optimize the Turkish natural gas network system, give us effective and efficient results to forecast and construct the future configuration of the natural gas network more accurately with savings of money, time and effort.

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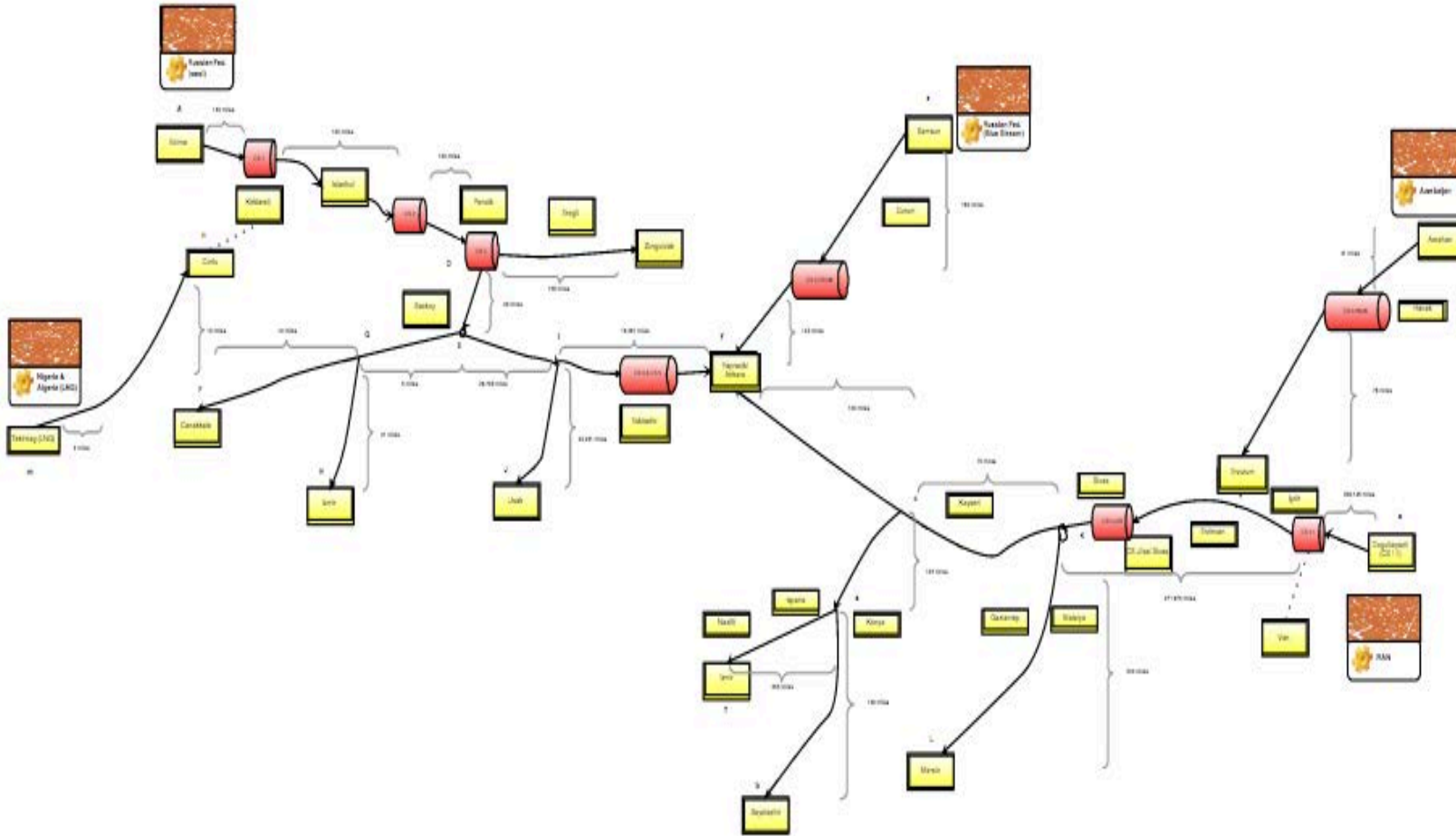
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APPENDIX A
ACRONYMS

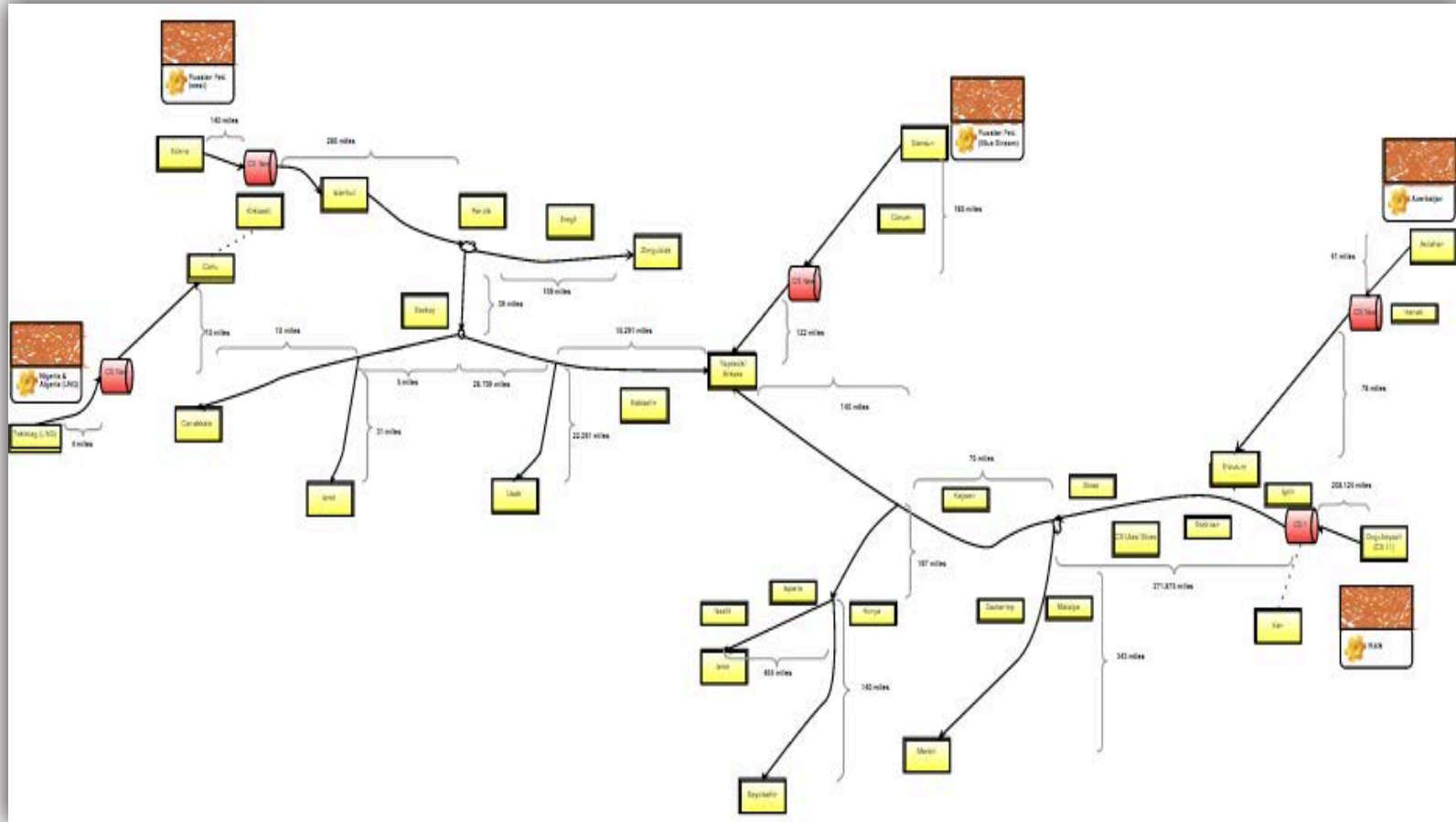|	
AER	American Economic Review
Bcf	One billion cubic feet
BOTAS	Turkish Petroleum Pipeline Corporation
BP	British Petroleum
CO2	Carbon dioxide
DOE U.S.	Department of Energy
EIA	Energy Information Administration
EIA	Energy Information Agency
EMRA	T.R. Energy Market Regulatory Authority
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System
GWh	Gigawatt-hour (one thousand megawatt-hours)
IEA	International Energy Agency
MENR	Ministry of Natural Resources
Mtep	Millions tons of equivalent oil
NG	Natural Gas
OECD	The Organization for Economic Co-operation and Development
SEEP	South East European Pipeline
TANAP	Trans Anatolian Pipeline
TPAO	Turkish Petroleum Corporation
USSR	Union of Soviet Socialist Republics

APPENDIX B

Current Map of Natural Gas Transmission System in Turkey

Final Optimal Network of Natural Gas Transmission System in Turkey (Model 1)

Final Optimal Network of Natural Gas Transmission System in Turkey (Model 2)