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ALTERNATE MODELS FOR NATURAL GAS TRANSPORTATION SYSTEM PERFORMANCE OPTIMIZATION

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ALTERNATE MODELS FOR NATURAL GAS TRANSPORTATION SYSTEM PERFORMANCE OPTIMIZATION

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Manufacturing Systems Engineering in the
College of Engineering at the University of Kentucky

By

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ABSTRACT

ALTERNATE MODELS FOR NATURAL GAS TRANSPORTATION SYSTEM PERFORMANCE OPTIMIZATION

The Natural Gas market in the U.S is growing rapidly with evidence that the nation has enough shale reserves to power the country for the next century. To ensure continued economic benefits through the use of this environmentally desired energy source, it becomes important to optimize the transportation network system design. Transportation through pipelines is one of the most common methods used to distribute Natural Gas from source to destination. This transportation system, consisting of pipelines, compressors and other supporting equipment, must be optimized, considering all relevant parameters to minimize cost and increase profit. The research presented here improves on the fuel cost minimization models in literature to incorporate pipeline elevation and safety requirements. A new model is proposed to consider the entire transportation network as a single system and optimize it considering all relevant parameters. The optimization model is setup as a mixed integer nonlinear program. The proposed model is used to optimize the pipeline network for a case study, evaluate the model as well as investigate design capacity and installed capacity of pipeline network.

KEYWORDS: Natural Gas, Pipelines, Fuel Cost, System Cost

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ALTERNATE MODELS FOR NATURAL GAS TRANSPORTATION SYSTEM PERFORMANCE OPTIMIZATION

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I thank my employers – Nabors Drilling and National Oilwell Varco for providing me the opportunity to understand the Oil and Gas Supply Chain in general and extraction in specific.

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CHAPTER 1

INTRODUCTION TO NATURAL GAS

1.1 History to Natural Gas

Natural Gas, is a colorless, odorless and tasteless combustible gas. It is considered as the ideal fossil fuel because, it gives off less emissions compared to any other fossil fuel when burnt. Natural Gas is also much safer to transport and store compared to other fuel.

Methane (CH_4) is the major constituent of Natural Gas. The other constituents of Natural Gas are Ethane (C_2H_6), Propane (C_3H_8), Butane (C_4H_{10}), Pentane (C_5H_{12}), etc. When extracted from the ground, Natural Gas contains impurities like H_2O, H_2S, CO_2, etc. which have to be removed before the gas is used as a fuel.

In 1000 B.C, Natural Gas was discovered during a lightning strike, which caused it to seep out through the earth’s surface. This appears as a spring of fire commonly known as a “burning spring”. One of the most popular burning springs was found in Greece on Mount Parnassus, now known as Oracle of Delphi. These types of springs were observed in Greece, India and Persia (Natural Gas.org, 2013a).

In 500 B.C the Chinese were the first to capture and use Natural Gas as a fuel for cooking by transporting them through bamboo pipelines. While the British were the first to commercialize its use in 1785, the commercial use of Natural Gas began in the U.S in 1816, as a source of energy to light streetlights in Baltimore, Maryland (Natural Gas.org, 2013a).

1.2 Importance of Natural Gas

Natural Gas is used to power more than one half of the energy consumed by the residential and commercial users; it also satisfies about 41% of the energy used in the U.S. industries (American Public Gas Association, n.d). Hence, Natural Gas is of high significance both from an economic perspective and environmental perspective due to the lower emissions generated.

1.2.1 Natural Gas U.S Demand

The U.S. Natural Gas production has seen steady growth since 2006 as shown in Figure 1.1. The production of Natural Gas has grown from 19 Trillion Cubic Feet (Tcf) in 2006 to 25.7 Tcf in 2013, a growth of 36% over the last eight years (U.S. Energy Information Administration, 2014).

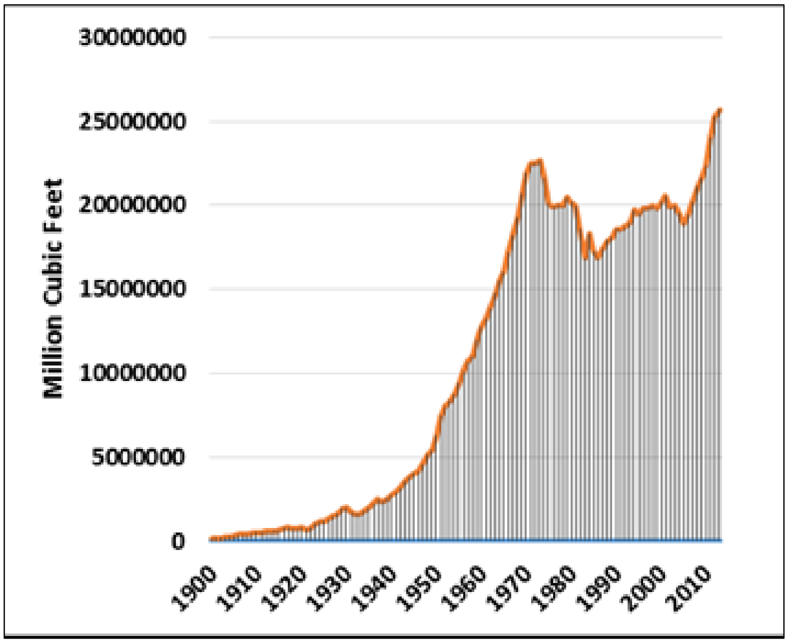


Figure 1.1: U.S Natural Gas Production

The American Gas Association reported in 2011 that the current U.S Natural Gas reserves are as high as 300 Tcf (American Gas Association, 2012), while a different study reported in a recent MIT report (American Gas Association, 2012) states the availability of 2,100 Tcf of Natural Gas, a much higher estimate, based on reserve information and future reserve assessment. This means that U.S potentially has enough Natural Gas to power her for the next 92 years based on 2009 consumption.

While the usage of Natural Gas to generate electricity has grown by 119% from 2000 to 2012 (U.S. Energy Information Administration, 2015), the discovery of the new shale formations guarantees the growth of the use of Natural Gas to produce electricity.

1.2.2 Natural Gas Global Demand

The International Energy Agency's world energy outlook annual report projects that the global usage of Natural Gas as an energy source will grow until 2035 (International Energy Agency, 2011). Figure 1.2 shows this projected usage (measured in million ton of oil equivalent) of energy source/fuel type to meet global energy requirements from 1980 through the next 20 years (International Energy Agency, 2011). The average annual growth rate between 2009 and 2035 of usage of Coal, Oil and Natural Gas are 0.8%, 0.6% and 1.7% (International Energy Agency, 2011), respectively affirming the significance of Natural Gas as potential and preferred source of energy, that can be used to meet the energy needs of the U.S and rest of the world.

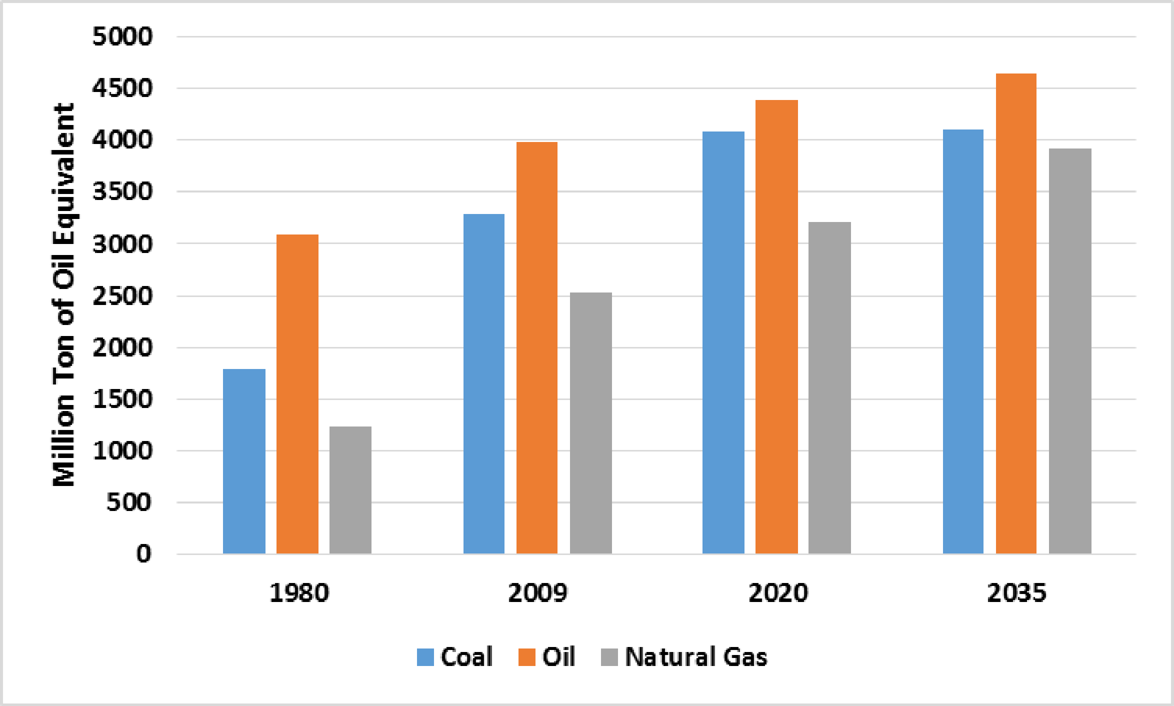


Figure 1.2: Global Energy Production Forecast by Fossil Fuel Type

1.3 Natural Gas Supply Chain

The Natural Gas supply chain consists of four phases – Exploration, Extraction, Processing, Transportation and Marketing schematically shown in Figure 1.3. Each of the phases is described in detail in the section below.

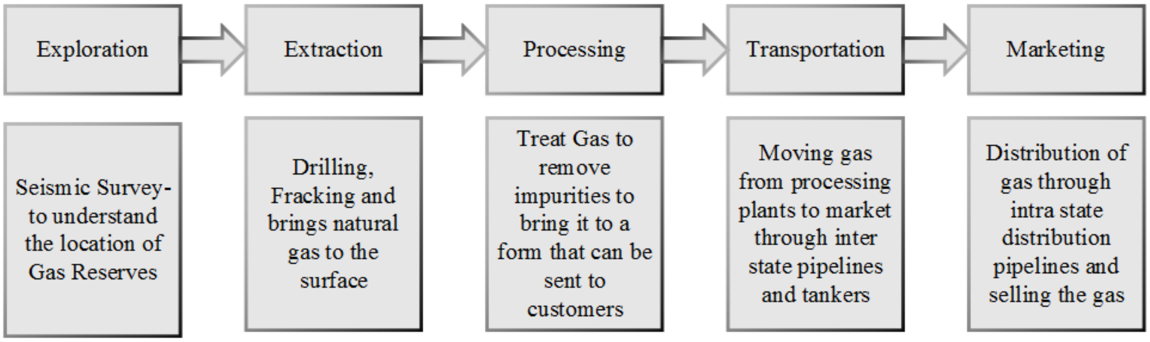


Figure 1.3: Natural Gas Supply Chain

1.3.1 Exploration

Exploration is the process of finding the coordinates of the location of the Natural Gas on the earth's surface. Geologists determine the location of underground fossil fuel reserves by examining the cap rock in the location. They compare it with the samples obtained from previous reserve locations to determine the underground formation in the location. Then, advanced tools such as seismic surveys are used to get further details about the formation.

1.3.2 Extraction

Once the site that consists of a large deposit of Natural Gas is identified, the next step is extraction. Extraction is the process of bringing the Natural Gas to the surface. This includes two steps namely drilling, completions and production. Drilling is the process of drilling the well using drill rigs. Before the drilling begins, environmental clearance must be obtained. Completions is the process of preparing the drilled well to produce Oil/Natural Gas. Completions includes fracturing the Natural Gas sediments using perforation guns and Fracking, which is the process of using Fracking fluid to extend and expand the cracks created using the perforation gun and keeping them open. Completions is followed by production, where Natural Gas is brought to the surface by natural and artificial means.

The global rig count over the years in shown in Figure 1.4 (Petroleum Online, n.d). The trend reveals an increase in rig count, when the oil price stabilizes, though a drop is observed in 2013 due to the decline of oil prices. The general trend, however, is an increase in the global drilling rigs over the past one and a half decades, reiterating that the demand for Oil and Gas in general and particularly for Gas is increasing. Also, more than half the global drill rigs were located in the U.S. (Petroleum Online, n.d).

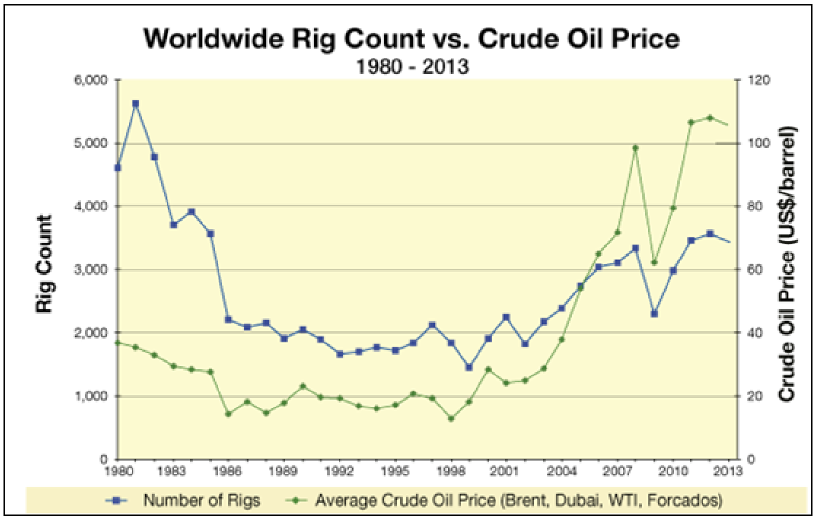


Figure 1.4: Worldwide Rig Count vs. Crude Oil Price

1.3.3 Processing

During production, the gas flows to the surface. This is collected and taken to the processing plant by gathering pipelines which generally connect multiple wells. At the processing plant, the crude Natural Gas is treated to remove all the impurities mentioned in the previous section, making it a commercially usable Natural Gas.

1.3.4 Transportation

After Natural Gas is refined, it is transported through interstate pipelines to the market. This transportation system for carrying the Natural Gas through large diameter pipelines under high pressure consists of various components namely pipelines, valves, regulators, compressors, pressure gauges, storage facilities, etc. The Natural Gas pipeline system is explained in detail in Section 1.4. With the decrease in the oil price, the transportation of Natural Gas will tend to switch more towards pipeline transportation since it is the cheaper alternative.

1.3.5 Marketing

In the Natural Gas industry, the distribution of Natural Gas from the interstate pipelines to districts is called marketing. The delivery point of interstate pipelines are usually distribution companies that distribute the Natural Gas through smaller distribution pipelines to individual customers who are usually residential, commercial places and industries.

1.4 Natural Gas Pipeline System

The transportation of Natural Gas from the production region to the customer takes place through a complicated network of pipelines. Figure 1.5 (U.S. Energy Information Administration, n.da) shows the schematic of Natural Gas transmission path. The most commonly used means to transport Natural Gas are the pipelines that run along the length and breadth of the nation. Four major types of pipelines widely used are flowlines, gathering pipelines, transmission pipelines and the distribution pipelines.

Flowlines are relatively narrow pipelines that operate at 250 psi and connect the well head to the gathering pipelines. The gathering pipelines are those used to collect Natural Gas from the flowlines and deliver the gas to the processing plants for refining. These are small diameter pipelines (typically 18” or less) which operate at pressure of about 715 psi. The distribution pipelines generally consist of the main and service pipelines. The main pipelines are those that carry the gas from the interstate pipeline and run through the district. The distribution pipelines carry gas at low pressure of 2-15 bar (30-218 psi) (Sanchez, 2010).

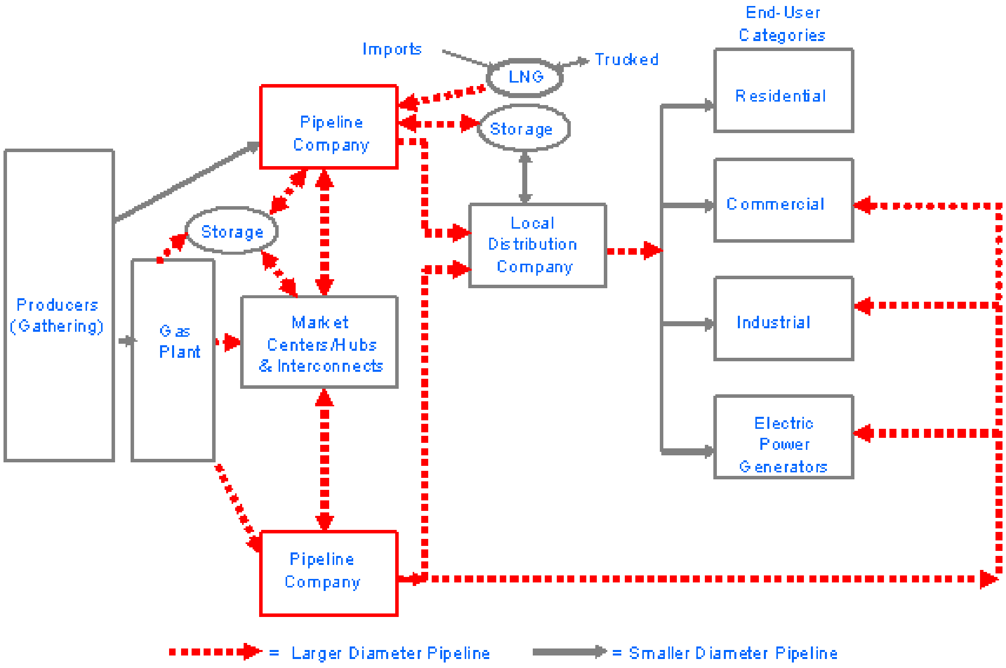


Figure 1.5: Natural Gas Transmission Path

The transmission pipelines carry large volumes of Natural Gas at high pressure (200 to 1500 psi) and are most often used for interstate transmission. They are large diameter pipelines with inner diameter of 6 to 48 inch. Most major interstate pipelines are 24 to 36 inch in diameter. They are made of either carbon steel or highly advanced plastics (Natural Gas.org, 2013b).

1.5 Pipeline System Support Equipment

There are various supporting equipment/facilities in the Natural Gas pipeline system that enable the system to serve its purpose of delivering the gas to the right location in the right quantity and pressure. Some of the major support equipment/facilities are Compressor Stations, Metering Stations and Flow Control Valves.

Natural Gas flows through the pipeline because of the pressure of the gas. As the gas moves through the pipeline, there is a drop in pressure and energy due to the following:

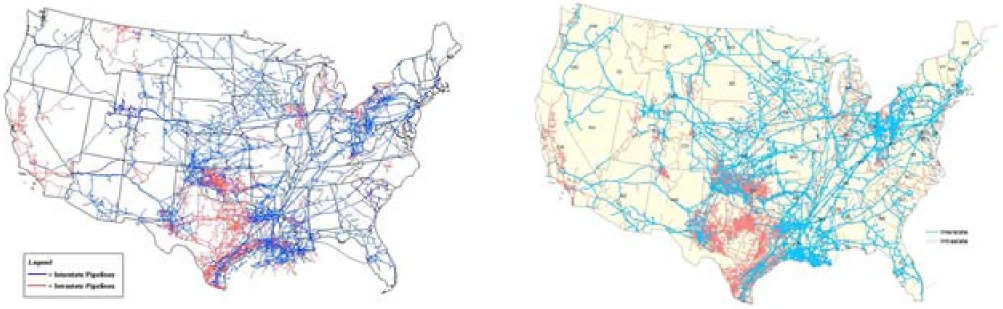
1. Friction between the Natural Gas and the inner walls of the pipe
2. The heat loss due to convection.

This energy and pressure drop is restored using compressor stations distributed across the network. Typically a compressor station is located every 30 to 50 miles to serve this purpose. Based on the volume of flow through the pipeline the number of compressors can vary from a few to a very large number. The compressors use the gas from the pipeline as fuel to make up for lost energy and pressure. This gas consumption of as fuel varies from 3% to 5% of the total gas flow through the pipeline (Wu et al, 2000; Sanchez & Mercado, 2009).

Compressor stations are complicated systems consisting of multiple types of compressors and configurations. In industry, two types of compressors are widely used: reciprocating compressors and centrifugal compressors. The major factors that affect the compressor station cost are – capital cost, operations cost, availability, life cycle cost and emissions (Kurz et al., 2011). Metering stations to measure flow and gate valves to control flow are distributed throughout the pipeline system.

1.6 U.S Natural Gas Transmission System

The expansion of U.S interstate and intrastate pipelines from 2009 and 2013 is clearly visible from the network shown in Figure 1.6 (U.S Energy Information Administration, n.db).



(a) U.S Pipeline Network in 2009 (b) U.S Pipeline Network in 2013

Figure 1.6: U.S Natural Gas Pipeline Network

In 2014, 20 new projects were in progress that covers 3,859 miles of pipelines and 22,574 MMcf/D capacity (U.S Energy Information Administration, n.dc). Also, there were expansion projects covering 779 miles of pipelines and 9,714 MMcf/D capacity (U.S Energy Information Administration, n.dc).

Major investments have been made in the U.S Natural Gas transportation system in recent years. These are likely to grow in future years given the economic and environmental benefits of using the Natural Gas as a source of energy. The complexity of the transportation network and the conflicting objectives of the stakeholders underscores the need for more effective decision support tools to design networks and improve performance.

1.7 Current State of Art and Research Gap

As discussed previously, the current and future production volume of Natural Gas favors transportation through pipelines because of economic benefits. A few years ago, the pipeline companies bought Natural Gas from the source and sold them to operating companies. The objective of the transportation companies was to maximize flow and optimize the schedule in order to maximize the revenue. In literature, Sanchez and Haugland (2010, 2011), Romo et al., (2009) and Tomasgard et al., (2009) presented models that can be used to maximize the flow. These will be discussed in the following sections.

In the U.S, the bundling of Natural Gas ownership and transportation by a single company led to the situation where the pipeline companies can manipulate the oil price by controlling the quantity of oil and gas transported – using the supply and demand effects. Hence, regulations unbundled the oil and gas ownership from transportation, opening the market to third party transportation companies. As a result of the unbundling, the objective of the transportation companies shifted from flow maximization to cost minimization. Hence, the flow maximization model that exist in the literature cannot be used in the U.S market, and there is a need for cost minimization models.

The compressors use 3% to 5% of the total Natural Gas that flows through the pipeline (Wu et al., 2000; Sanchez & Mercado, 2009). This means that 25.7 Tcf of Natural Gas is produced every year in the U.S (U.S. Energy Information Administration, 2014) of which almost 1.28 Tcf is geing consumed to transport gas. The scale of operation of Natural Gas transportation through pipelines in the U.S. is large enough that even a small improvement can result in a significant savings. Hence, it is important to optimize the transportation of Natural Gas through the interstate pipeline system, which can provide the opportunity to save millions of dollars. Sanchez and Haugland (2009) and Chebouba et al., (2009) have used Tree decomposition and Ant Colony algorithms, respectively, to focus on fuel cost minimization. Wu et al. (2000) is the most notable research in this area. Other literature that has focused on the fuel cost minimization are (Mercado et al., 2006; Abraham & Amin, 2010; Sanaye & Mahumoudimehr, 2012; Jamshidifar, 2011; Sanchez & Haugland, 2011c). These studies are discussed in detail in the literature review section.

There are many other costs in addition to the compressor station fuel consumption which play a critical role in determining the financial performance of the transportation system. These are compressor maintenance cost, pipeline capital cost and compressor capital cost. Thus, it is important to determine the transportation system configuration that minimizes both the fuel cost and all other cost associated including the pipeline infrastructure cost.

Based on the literature reviewed, there is currently no optimization model that focus on both fuel cost minimization and pipeline system cost minimization.

1.8 Research Objectives

After liberalization, the focus of Natural Gas transmission pipeline companies has shifted from flow maximization to cost minimization. In literature, there are models available to minimize the fuel cost of the compressor stations. Based on the literature reviewed, in the models available in literature for fuel cost minimization, critical constraints like pipeline elevation and maximum allowable operating pressure (MAOP) have not been considered. Hence, the first research objective of this research is to propose a modified compressor fuel cost minimization model that considers the MAOP and pipeline elevation. To address gap in literature on pipeline network cost minimization model, the second research objective is to develop an optimization model that can be used to minimize the entire pipeline network cost including compressor fuel cost, compressor maintenance cost, pipeline capital cost and compressor capital cost, by selecting the optimal values for selection and location of compressors, diameter of pipeline and pipeline inlet pressure.

The final research objective is to demonstrate the application of the model to a specific case of a real world Natural Gas transportation pipeline network to verify the model as well as critique the network design for its feasibility to achieve performance goals.

1.9 Thesis Organization

This thesis is organized into 6 chapters. Chapter 1 explains the importance of the Natural Gas, the growth of U.S Natural Gas market, cost components of the Natural Gas transmission network and the research objectives. Chapter 2 explains the literature available about Natural Gas optimization models. Chapter 3 describes the fuel cost minimization model that exists in literature. It also proposes a modified fuel cost minimization model that considers MAOP and pipeline elevation. An example mentioned in (Wu et al., 2000) is solved using the model proposed, considering zero elevation to compare the results of the model proposed with the model that exists in the literature and check the functionality of the proposed model. Chapter 3 also discusses the drawbacks of the fuel cost minimization model. In Chapter 4, a model is proposed to minimize the overall pipeline network cost.

The model proposed in Chapter 4 is used to solve a special case of a real world Natural Gas transportation network, using commercially available packages in Chapter 5.

The conclusion of the research and the recommendations for future work in the Natural Gas transmission network is explained in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

There are many types of optimization models and techniques available to study and evaluate Natural Gas pipeline operations. As mentioned in the previous section, the models are for either flow maximization or fuel cost minimization; scheduling models are also used in the Natural Gas operations management. The literature available in these areas are presented below.

2.1 Optimization Models for Flow Maximization

Romo et al., (2009) have used GassOpt on the Natural Gas Transmission of the Norwegian Continental Shelf, with 4,850 Miles of subsea pipelines, the world's largest pipeline network (Romo et al., 2009). SINTEF has developed GassOpt, a decision support toll which is based on mixed-integer program, to optimize the network configuration and routing of the mainstream pipelines. GassOpt allows users to graphically model their network and run optimization to find the best solutions quickly. Using of graphical/simulation software and combining them with optimization techniques to find the optimal solution is becoming a growing practice in the modern world. This literature has considered the Supply and Demand node capacity, the mass balance the pressure and volumetric split to come up with the flow maximization optimization model with important given to quality of the gas. . But the need in the current U.S market is cost minimization model. Hence this model will not be usable in the current U.S market. From this literature, it was found that the Oil and Gas companies like StatoilHydro (now known as Statoil) are interested in simulation based optimization which let to further interests in researchers in building models which are based on simulation and optimization (Romo et al., 2009). Hence, evaluating the optimization methods used in the current leading simulation software – OptQuest, which comes preloaded with Arena and SIMUL8 has become one of the research objectives of this thesis.

Sanchez and Haugland (2010) has investigated the flow maximization problem for Natural Gas Pipeline Transportation. The flow of Natural Gas into pipeline happens at different entry points and they will have different specific gravity. According to Sanchez and Haugland (2010), this factor is not considered in the early literature and hence, Sanchez and Haugland (2010) has improvised the previously existing model to incorporate these by modeling the flow capacity as a function of compressibility and gas specific gravity. In Sanchez and Haugland (2010) the specific gravity of Natural Gas is considered to be the weighted average of the specific gravity of Natural Gas at all the entry points. This model is based on a mixed-integer nonlinear program which is solved using heuristic approach. This is a good method to maximize the flow while considering variable specific gravity.

Sanchez and Haugland (2011b) aimed to develop a model to handle load fluctuations in the pipeline system. This model improvised on the model proposed in Sanchez and Haugland (2010) by added line-pack (storage), which resulted in a model that considers seasonal demands and optimize the flow. This model is based on mixed model non-linear programing. Both of these models are not applicable in the current U.S market where the objective is cost minimization.

Tomasgard et al., (2007) uses a stochastic portfolio programming to explain modeling of the Natural Gas Supply Chain including production, transportation, processing, contracts and markets and gives insight of the importance of Natural Gas supply chain and the complexity involved in designing it. It also explains how optimization can help decision makers of Natural Gas operating companies in making decision on difficult activities. In this model, a penalty cost is added for deviation from contracted quality and pressure level. It explains the use of linearized model based on mixed integer programming to optimize routing of Natural Gas to maximize flow. This model considers contract pressure, a critical factor which has not been considered in the previous models. Once again, this model cannot be used for the current U.S market because of the difference in objectives.

From the above researched, it has been identified that the Natural Gas transportation through pipeline problem should be a mixed-integer nonlinear program.

2.2 Optimization Models for Fuel Cost Minimization

The first notable fuel cost minimization model of steady state gas pipeline networks was proposed by Wu et al. (2000). In this work, the decision variables considered are the pressure drop at each of the nodes, mass flow rate at each nodes and the number of units operating within each compressor stations. The constraints of this model are then relaxed to find the optimal solution in shorter time. The two relaxations are on the feasible compressor domain and the other is on the fuel cost function to derive the lower bounding scheme. This is the model which is used as a major reference in the literature on fuel cost minimization, which were created later on. In this model, factors including the effect of pipeline elevation, MAOP, which are of high significance in the Natural Gas transportation model were not considered. This is the major reference in our investigation on fuel cost minimization model. The compressor operating domain constraints used in this model were proposed in (Percell & Ryan, 1987). Wu et al., (2000) has also proposed the fuel cost function.

Mercado et al., (2006) used a heuristics based solution method for the model that was developed in Wu et al., (2000). This heuristic method is based on two-stage iterative procedure. In the first stage, the gas flow variables were fixed and the optimal pressure variables are found using dynamic programming. In the second stage, the pressure variables were fixed the flow variables were modified to find the optimal value of the objective function. This model has the same drawbacks as Wu et al., (2000). Also, this method is iterative which adds to the complexity and increases the processing time.

Sanchez and Mercado (2009) used a hybrid metaheuristic procedure to solve the model developed in Wu et al., (2000), to exploit the problem structure efficiently. This hybrid metaheuristic uses dynamic programming algorithm for finding the optimal values for the pressure nodes for a given mass flow rate and a short term memory Tabu search algorithm to guide the search to find the best possible value for the flow variables. This work also generalizes that the Tabu search procedure outperforms the multi start GRG both in quality and feasibility. This reiterates that using OptQuest, which uses Tabu search, in the new model that is proposed in this thesis work can contribute to improving solution search.

The model proposed in (Wu et al., 2000), was solved using Tree decomposition in (Sanchez & Haugland 2009; Sanchez & Haugland 2010). In these work, the authors were able to construct tree decomposition and apply dynamic programming to solve the discrete version of the pressure optimization problem without analyzing the whole solution space. The drawbacks of (Wu et al., 2000) also apply to these literature.

Chebouba et al., (2009) used Ant Colony Optimization (ACO) algorithm to solve the gas transportation through pipeline problem to minimize the fuel cost. This research concluded that the Ant Colony Optimization algorithm is better than dynamic programming for the Natural Gas transportation system fuel cost optimization problem. The decision variables, similar to previous studies are used - the number of compressors used and the discharge. In this literature, the authors used a model which is similar to (Wu et al., 2000) and hence the same drawback exists.

Abraham and Amin (2010) used a visual C++ code which is based on Newton-Rephson technique to solve the Gas Transportation Problem to minimize the fuel cost. In this research, simulation is used to find the optimal solution. The model used in this is also similar to (Wu et al., 2000).

Jamshidifar (2011) and Sanaye and Mahmoudimehr (2012), used Genetic Algorithms to solve the previously discussed model. They found that the Genetic Algorithm method can be used to solve Natural Gas Transportation Pipeline network, ranging from simple to complex network, in the shortest time. Sanaye and Mahmoudimehr (2012) also says that, while the computing time for a non-sequential dynamic programming (NDP) method varies exponentially with the step size of pressure and flow rate, the computing time of Genetic Algorithm is independent of the step size.

In all the above said literature, bypassing any compressor station is not allowed. However in real world networks, the compressor stations can be bypassed.

2.3 Scheduling Optimization Models

There are work done in the area of scheduling of gas flow where a Genetic Algorithm is used. Ribas and Yamamoto (2013), breaks-down the scheduling problem into three sub problems – assignment of resources, sequencing of activities and determining the resource timing utilization by the activities. This method used a hybrid approach based on Genetic Algorithm and mixed integer programming. In this research, a micro generic algorithm is also proposed to reduce the processing time required to find the optimal solution and the values of decision variables. This model is based on flow rate control/scheduling but does not consider cost minimization. Hence this cannot be used for the current U.S market.

2.4 Other Optimization Models

Nguyen and Chan (2005) focused on optimizing the pipeline operation by scheduling the compressors while minimizing the horsepower requirement. The author has used Neural Networks to search for the best forecasting of load and Genetic Algorithm to find the optimal combination of the compressors. The result obtained was compared with fuzzy programming model to conclude that generic algorithm works better than the fuzzy programming.

Wu et al., (2014) created a model to maximize the flow while minimizing the horsepower requirement. This model was solved using Swarm Optimization Algorithm and is well suited for finding a balance between pipeline's operating profit and transported amount of Natural Gas. Goldberg (1987) created a model which minimizes the horsepower requirement to transport Natural Gas through pipeline using Genetic Algorithm.

The other notable work done in the area of Natural Gas Transmission Pipeline optimization are Manidi et al., (2009) where distribution is optimized and Ozelkan et al., (2008) where the cost minimization is done for Natural Gas transportation through tankers. Zheng et al., (2010) have summarizes some of the optimization algorithms in the Natural Gas supply chain. The above mentioned literatures and models are useful for markets where bundling of Natural Gas and its transportation is present. However, in the current U.S market, these models do not favor since the object of the U.S Natural Gas Transportation companies is to minimize cost.

2.5 Inference from Literature

From the literature, it is understood that Natural Gas Pipeline System models are Mixed Integer Non Linear Program (MINLP), which cannot be solved using analytical methods and hence GA, which has been used to solve Natural Gas optimization models in the past is an effective algorithm for the Natural Gas optimization models. Also, usage of simulation software and combining optimization algorithm with the simulation software is becoming a growing practice (Romo et al., 2009). Hence Genetic Algorithm and OptQuest, the optimization algorithm used in the popular simulation software packages are used to solve the proposed model and to understand which of the two algorithms is better suited to the Natural Gas Transportation systems optimization.

In the fuel cost minimization problem, it has been observed that the compressors used are considered to be identical (Sanchez & Haugland, 2009; Sanchez & Mercado, 2009; Chebouba et al., 2009; Abraham & Amin, 2010). Also, it is assumed that the Natural Gas flows through each of the compressor stations. However in the real world, these are not the case. In a compressor station there typically are multiple configurations of centrifugal compressors and the Natural Gas can bypass one or more compressor stations. Hence, the need for modeling multiple configurations of centrifugal compressors and compressor station bypass condition occurs. Also, it has been found that the current cost minimization models do not consider the entire pipeline system but considers only the compressor station. The Natural Gas Transmission System is a complex system and hence ignoring some of the operation parameters while minimizing the cost could cost millions of dollars. Hence, a model that studies Natural Gas Transmission as a holistic system while optimizing needs to be developed.

CHAPTER 3

FUEL COST MINIMIZATION PROBLEM

In the literature review and section 1.7, we discussed about the importance of fuel cost minimization and research done in the area of compressor station fuel cost minimization modelling was discussed. These models are focused on optimizing the compressor units/stations. In this chapter, the fuel cost minimization model that exists in the literature is presented and modification is proposed to incorporate the MAOP and pipeline elevation, which were not considered previously. The scenario in which the fuel cost minimization does not provide accurate results is also discussed.

3.1 Decision variables

The fuel cost in a compressor station depends on the suction pressure, the discharge pressure, speed of the compressors and the number of compressor units operating. Therefore, these are considered as decision variables. The decision variable in a compressor system with a set of nodes ‘a’, which determine the fuel cost are p_A, p_B , S_{ac} and N_a, are defined as follows.

p_A = Suction pressure at inlet node ‘A’, where ‘A’ $\in$ (a)

p_B = Discharge pressure at outlet node ‘B’, where ‘B’ $\in$ (a)

S_{ac} = Speed of compressor ‘c’ at node ‘a’, where 'c' ranges from 1 to n_a

N_a = Number of compressors selected to run at node ‘a’

3.2 Assumptions

The assumptions made in developing this model are listed below.

- All the compressors in a station take in gas at a constant pressure, compresses and pushes the gas out at a constant pressure.
- The operating condition of the Natural Gas Transmission systems is assumed to be steady state and isothermal.
- The compressors at each of the compressor stations are assumed to be of same type.
- Natural Gas flows through every compressor station.
- The volumetric flow rate through each of the selected compressors are equal.
- The compressibility and specific heat of the Natural Gas is assumed to be constant

3.3 Performance Parameters of a Compressor

The parameters that describe the condition of flow of Natural Gas through a compressor are:

- Pipeline Inlet pressure p_a (psig) at node 'a'
- Pipeline Outlet pressure p_b (psig) at node 'b', where $b = a+1$ and
- Mass flow rate through compressor X_{ac}

These flow parameters can be controlled by changing the compressor parameters namely compressor speed S_{ac} (rpm) and adiabatic head H_a (Wu et al., 2000).

In this model (Wu et al., 2000), there are multiple nodes, which can be either compressor nodes, inlet nodes, outlet nodes or branching nodes. The compressor nodes are the nodes in which compressor stations are present. The inlet nodes are the nodes which are connected to the source or storage of Natural Gas. The outlet nodes are the nodes that are the demand points. The branching nodes are the nodes in which the pipe line split into branches or join from branches. At node 'a', for compressor 'c', the parameters that affect the performance of the compressor are shown in Table 3.1.

Table 3.1: Performance Parameters of a Compressor

Parameters	**Notation**
Volumetric flow rate through the compressor 'c' at node 'a' (MMscf/D)	Q_{ac}
Mass flow rate through the compressor 'c' at node 'a'	X_{ac}
Compressor suction pressure at node 'a'	sp_{ac}
Compressor discharge pressure at node 'a'	dp_{ac}
Number of compressor at node 'a'	n_a
Adiabatic head at node 'a'	H_a
Adiabatic efficiency of compressor 'c' at node 'a'	η_{ac}

The above parameters are related to each other by the following set of equations (Percell & Ryan, 1987) and (Zheng et al., 2010).

$$\frac{H_a}{S_{ac}{}^2} = A_H + B_H\left(\frac{Q_{ac}}{S_{ac}}\right) + C_H\left(\frac{Q_{ac}}{S_{ac}}\right)^2 + D_H\left(\frac{Q_{ac}}{S_{ac}}\right)^3 \qquad \forall\,(a, c) \rightarrow \qquad (1)$$

$$\eta_{ac} = A_E + B_E\left(\frac{Q_{ac}}{S_{ac}}\right) + C_E\left(\frac{Q_{ac}}{S_{ac}}\right)^2 + D_E\left(\frac{Q_{ac}}{S_{ac}}\right)^3 \qquad \forall\,(a, c) \rightarrow \qquad (2)$$

$$H_a = \frac{ZRT_B}{m}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^m - 1\right] \qquad \forall\,(a, c) \rightarrow \qquad (3)$$

$$Q_{ac} = ZRT_B \left(\frac{X_{ac}}{p_a}\right) \qquad \forall\ (a, c) \rightarrow \qquad (4)$$

Where Z, R, T_B are constants. A_H, B_H, C_H, D_H, A_E, B_E, C_E, D_E are compressor specific parameters.

Equation (1) shows the relation between the adiabatic head, volumetric flow rate through the compressors, the speed of the compressor and the compressor specific parameters. Equation (2) shows the relation between the volumetric flow rate, speed of compressor, compressor adiabatic efficiency and the compressor specific parameters. Equation (3) is the calculation to find the adiabatic head and equation (4) is the relation between the volumetric flow rate and mass flow rate.

3.4 Objective Function

The objective is to minimize the fuel cost related to all the compressor units in the network. The general fuel cost function of a single compressor is given by (Wu et al., 2000) as follows.

$$\text{Fuel cost} = \frac{M * X_{ac}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^{m} - 1\right]}{\eta_{ac}} \qquad \forall\ (a, c) \rightarrow \qquad (5)$$

Where,

M = constant

X_{ac} = mass flow rate through compressor ‘c’ at node ‘a’

m = (k-1)/k (Menon & Menon, 2013)

k = specific heat ratio

For the entire compressor network, given ‘N’ compressors selected in a station, the objective function will be modified as follows.

$$\text{Fuel cost for a compressor} = \frac{M * X_{ac}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^{m} - 1\right]}{\eta_{ac}} \qquad \forall\ (a, c) \rightarrow (6)$$

$$\text{Fuel cost for a compressor station} = \sum_{c=1}^{N}\left[\frac{M * X_{ac}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^{m} - 1\right]}{\eta_{ac}}\right] \qquad \forall\ (a, c) \rightarrow (7)$$

If there are ‘E’ compressor stations in the network, the objective function will be modified as follows.

$$\text{Fuel cost of network} = \sum_{j=1}^{E}\left\{\sum_{n=1}^{N}\left[\frac{M * X_{ac}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^{m} - 1\right]}{\eta_{ac}}\right]\right\} \qquad \forall\ (a, c) \rightarrow (8)$$

3.5 Constraints

The various constraints in this model are the feasible operating domain of a single compressor unit, which is the region in which the compressor can function. The other constraints involved are the speed and adiabatic head of the compressors, volumetric flow constraint which is crucial for surge and stonewall and finally, the pressure loss governing equation.

3.5.1 Feasible Operating Domain of a Single Compressor Unit

The feasible operating domain of a single compressor unit is explained above in equation (1) and (2), and is once again shown below.

$$\frac{H_a}{S_{ac}{}^2} = A_H + B_H\left(\frac{Q_{ac}}{S_{ac}}\right) + C_H\left(\frac{Q_{ac}}{S_{ac}}\right)^2 + D_H\left(\frac{Q_{ac}}{S_{ac}}\right)^2 \qquad \forall\ (a, c) \qquad \rightarrow \qquad (1)$$

$$\eta_{ac} = A_E + B_E\left(\frac{Q_{ac}}{S_{ab}}\right) + C_E\left(\frac{Q_{ac}}{S_{ab}}\right)^2 + D_E\left(\frac{Q_{ac}}{S_{ab}}\right)^2 \qquad \forall\ (a, c) \qquad \rightarrow \qquad (2)$$

Equations (9) and (10) explains the lower and upper limit of the compressor speed and the head on which the compressor can operate.

$$\mathrm{S_{ac}\,L} \leq \mathrm{S_{ac}} \leq \mathrm{S_{ac}U} \qquad \forall\,(a, c) \qquad \rightarrow \qquad (9)$$

$$\mathrm{H_{ac}\,L} \leq \mathrm{H_{ac}} \leq \mathrm{H_{ac}U} \qquad \forall\,(a, c) \qquad \rightarrow \qquad (10)$$

Equation (11) explains the feasible suction pressure of the individual compressor units.

$$\mathrm{p_{ac}\,L} \leq \mathrm{p_{ac}} \leq \mathrm{p_{ac}U} \qquad \forall\,(a, c) \qquad \rightarrow \qquad (11)$$

3.5.2 Volumetric flow constraint

The volumetric flow rate should be constrained by the surge and stonewall line.

The constraint is given below (Wu et al., 2000).

$$\mathrm{Q_{ac}\,min} \leq \mathrm{Q_{ac}} \leq \mathrm{Q_{ac}max} \qquad \forall\,(a, c) \qquad \rightarrow \qquad (12)$$

Also,

$$\left(\frac{\mathrm{Q_{ac}}}{\mathrm{S_{ac}}}\right)^{\mathrm{min}} \leq \left(\frac{\mathrm{Q_{ac}}}{\mathrm{S_{ac}}}\right) \leq \left(\frac{\mathrm{Q_{ac}}}{\mathrm{S_{ac}}}\right)^{\mathrm{max}} \qquad \forall\,(a, c) \qquad \rightarrow \qquad (13)$$

3.5.3 Non-negativity constraints

The decision variables and adiabatic head in this case cannot be negative in reality. Hence, the non-negativity constraints should be included as shown below.

$$\mathrm{p_A} \geq 0,\ \mathrm{p_B} \geq 0,\ \mathrm{S_{ac}} \geq 0,\ \mathrm{N_a} \geq 0,\ \mathrm{H_{ac}} \geq 0 \qquad \forall\,(a, c) \qquad \rightarrow \qquad (14)$$

3.5.4 Pressure drop governing equations

When Natural Gas flow through the pipeline, it loses pressure. The equation that governs the pressure loss in the pipeline is called as the flow equation. The flow equations are described in (Menon & Menon, 2013). The two most commonly used flow equation in literature are the Weymouth Equation and the general flow equation.

The Weymouth Equation as mentioned in (Menon & Menon, 2013) is shown below.

$$Q = 433.5 \text{ x } E \text{ x } \left(\frac{\mathbf{T}_B}{\mathbf{P}_B}\right) \text{ x } \left(\frac{\mathbf{p_a}^2 - \mathbf{p_b}^2}{\mathbf{G} * \mathbf{T}_f * \mathbf{L} * Z}\right)^{\mathbf{0.5}} \text{ x } D^{2.667} \qquad \rightarrow \qquad (15)$$

Where,

Q = Volume flow rate, standard cu.ft/day (scf/D)

E = Pipeline efficiency, a decimal value less than or equal to 1

G = Gas Gravity

Z = Compressibility Factor

P_B = Base pressure (psig)

T_B = Base Temperature, ºR (460 + ºF)

T_f = Average Flow temperature, ºR (460 + ºF)

L = Pipe segment length (miles)

D = Pipe segment inner diameter (inch)

The General flow equation is another flow equation that explains how the pressure changes in a fluid pipeline. The general gas equation is given below.

$$Q = 38.77 \text{ x } F \text{ x } \left(\frac{T_B}{P_B}\right) \text{ x } \left(\frac{p_a^2 - p_b^2}{G * T_f * L * Z}\right)^{0.5} \text{ x } D^{2.5} \quad \rightarrow \quad (16)$$

Where, ‘F’ is the Transmission Factor.

Transmission factor is given by $F = 2/\sqrt{f}$. Where, “f” is the Friction Factor.

Even though there are two widely used flow equations, in this model, we will be using the general flow equation since it is the flow equation that is widely used in the fuel cost minimization model of Natural Gas transmission network. .

3.5.5 Missing Links

Safety has always been a priority in Natural Gas transmission systems. Hence, operations cost should not be lowered at the cost of safety. When gas flows through pipe, a pressure is exerted on the inner walls of the pipe and is called the operating pressure, which is critical for safety considerations. The maximum allowable operating pressure (MAOP) (Tabkhi et al., 2009) is not considered in the models in literature.

The MAOP constraint can be formulated as shown below, where P_{MAX} is the maximum limit of the pressure that can occur at any given point in the network.

$$P_{MAX} \leq MAOP \quad \rightarrow \quad (17)$$

Another limitation with the model in literature is the assumption that the pipelines runs on a perfectly flat ground. In reality, this is not the case. Hence, the flow equation has to be modified to incorporate the elevation differences in the pipeline network.

The general flow equation (16) should be modified to account the elevation difference in pipeline network as explained in (Menon & Menon, 2013). The modified general flow equation is shown below.

$$Q = 38.77 \text{ x } F \text{ x } \left(\frac{\mathbf{T}_B}{\mathbf{P}_B}\right) \text{ x } \left(\frac{\mathbf{p_a}^2 - e^s \mathbf{p_b}^2}{\mathbf{G} * \mathbf{T}_f * \mathbf{L}_e * Z}\right)^{\mathbf{0.5}} \text{ x } D^{2.5} \qquad \rightarrow \qquad (18)$$

Where,

$$L_e = L\left(\frac{-1 + e^s}{s}\right)$$

$$s = 0.0375 \text{ x } G \text{ x } \left(\frac{\mathbf{H_2 - H_1}}{\mathbf{T}_f Z}\right)$$

s = Elevation Adjustment parameter, dimensionless

H_1 = Upstream Elevation (ft)

H_2 = Downstream Elevation (ft)

3.6 Mathematical Model

The mathematical model developed is a non-linear program. The mathematical model is shown below.

$$\text{Objective Function: Minimize } \sum_{j=1}^{E} \left\{ \sum_{n=1}^{N} \left[\frac{M * X_{ac}\left[\left(\frac{dp_{ac}}{sp_{ac}}\right)^{m} - 1\right]}{\eta_{ac}} \right] \right\} \qquad \forall\ (a, c)$$

Subjected to the following constraints

$$Q_a = 38.77 * F \text{ x } \left(\frac{\mathbf{T}_B}{\mathbf{P}_B}\right) \text{ x } \left(\frac{\mathbf{p_a}^2 - e^{s}\mathbf{p_b}^2}{\mathbf{G} * \mathbf{T}_f * \mathbf{L}_e * Z}\right)^{\mathbf{0.5}} * D^{2.5} \qquad \forall\ (a, c)$$

$$L_e = L\left(\frac{-1 + e^{s}}{s}\right)$$

$$s = 0.0375 \text{ x } G \text{ x } \left(\frac{\mathbf{H_2 - H_1}}{\mathbf{T}_f Z}\right)$$

$$\frac{H_a}{{S_{ac}}^2} = A_H + B_H\left(\frac{Q_{ac}}{S_{ac}}\right) + C_H\left(\frac{Q_{ac}}{S_{ac}}\right)^2 + D_H\left(\frac{Q_{ac}}{S_{ac}}\right)^2 \qquad \forall\ (a, c)$$

$$\eta_{ac} = A_E + B_E\left(\frac{Q_{ac}}{S_{ab}}\right) + C_E\left(\frac{Q_{ac}}{S_{ab}}\right)^2 + D_E\left(\frac{Q_{ac}}{S_{ab}}\right)^2 \qquad \forall\ (a, c)$$

$$S_{ac}L \leq S_{ac} \leq S_{ac}U \qquad \forall\ (a, c)$$

$$H_{ac}L \leq H_{ac} \leq H_{ac}U \qquad \forall\ (a, c)$$

$$p_{ac}L \leq p_{ac} \leq p_{ac}U \qquad \forall\ (a, c)$$

$$Q_{ac}\min \leq Q_{ac} \leq Q_{ac}\max \qquad \forall\ (a, c)$$

$$\left(\frac{Q_{ac}}{S_{ac}}\right)^{\min} \leq \left(\frac{Q_{ac}}{S_{ac}}\right) \leq \left(\frac{Q_{ac}}{S_{ac}}\right)^{\max} \qquad \forall\ (a, c)$$

$$p_A \geq 0,\ p_B \geq 0,\ S_{ac} \geq 0,\ N_a \geq 0,\ H_{ac} \geq 0 \qquad \forall\ (a, c)$$

$$P_{MAX} \leq MAOP$$

3.7 Numerical Evaluation

To ensure that the model with the MAOP constraint is working as desired, it was tested against the linear network problem of Wu et al. (2000). The parameters used are shown in Table 3.2. Since there are contract pressures involved in this network, the suction pressure at node 1 and discharge pressure at node 4 are considered as parameters and not as decision variables. The MAOP value used was 900 psig.

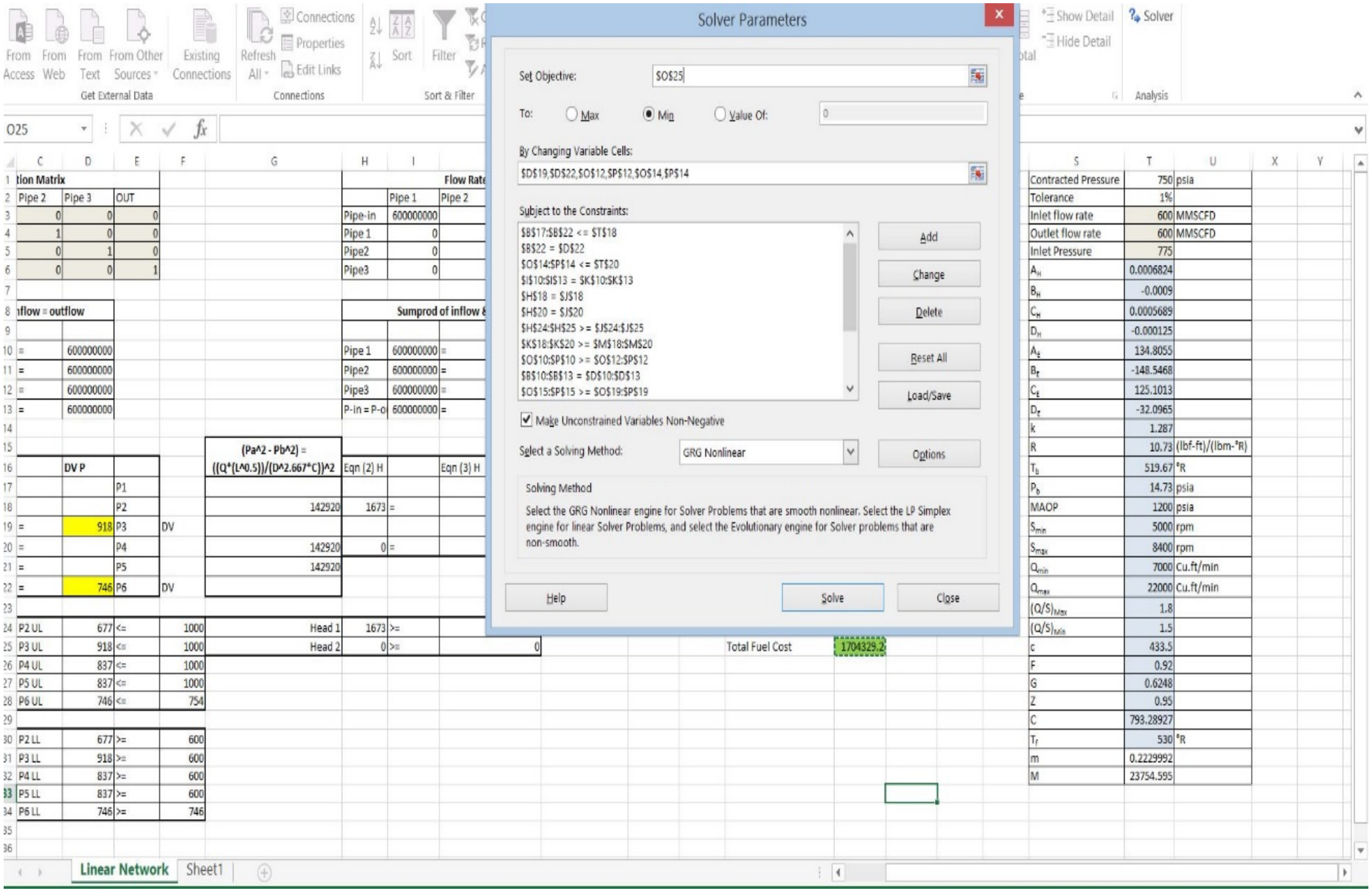
Table 3.2: Parameters Used for Numerical Evaluation

Parameter	**Value**
Q_{in}	600 MMscf/D
Q_{out}	-600 MMscf/D
sp_{ac}^{min}	600 psig
sp_{ac}^{max}	800 psig
dp_{ac}^{min}	600 psig
dp_{ac}^{max}	800 psig
Z	0.95
R	10.73 (lbf-ft)/(lbm-°R)
G	0.628
k	1.287
T_B	519.67 °R
A_H	0.6824×10^{3}
B_H	-0.9002×10^{-3}
C_H	0.5689×10^{-3}
D_H	-0.1247×10^{-3}
A_E	134.8055
B_E	-148.5468
C_E	125.1013
D_E	-32.0965
S_{min}	5000 RPM
S_{max}	8400 RPM
Q_c^{min}	7000 scf/M
Q_c^{max}	22000 scf/M

The model is designed as a linear network with 2 compressor station as shown in Figure 3.1. In this model, for validation purposes, the elevation of pipeline is not considered in order to compare results of the problem in Wu et al. (2000) with the model proposed.

Since the problem is non-linear, the Generalized Reduced Gradient (GRG) algorithm available in Microsoft Excel add-in, is used to solve the problem in a two-step process. The first step is to find a feasible solution. The second step is the usage of GRG algorithm to find the optimal solution. The user interface of the Solver add-in is shown in Figure 3.2. The general flow equation (16) is used in this model.

Figure 3.1: Schematic Representation of the Compressor Network Considered



Solver Parameters

Set Objective: $O$25

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells: $D$19,$D$22,$O$12,$P$12,$O$14,$P$14

Subject to the Constraints:

$B$17:$B$22 <= $T$18
$B$22 = $D$22
$O$14:$P$14 <= $T$20
$I$10:$I$13 = $K$10:$K$13
$H$18 = $J$18
$H$20 = $J$20
$H$24:$H$25 >= $J$24:$J$25
$K$18:$K$20 >= $M$18:$M$20
$O$10:$P$10 >= $O$12:$P$12
$B$10:$B$13 = $D$10:$D$13
$O$15:$P$15 >= $O$19:$P$19

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

S	T	U
Contracted Pressure	750	psia
Tolerance	1%	
Inlet flow rate	600	MMSCFD
Outlet flow rate	600	MMSCFD
Inlet Pressure	775	
A_H	0.0006824	
B_H	-0.0009	
C_H	0.0005689	
D_H	-0.000125	
A_E	134.8055	
B_E	-148.5468	
C_E	125.1013	
D_E	-32.0965	
k	1.287	
R	10.73	(lbf-ft)/(lbm-°R)
T_b	519.67	°R
P_b	14.73	psia
MAOP	1200	psia
S_{min}	5000	rpm
S_{max}	8400	rpm
Q_{min}	7000	Cu.ft/min
Q_{max}	22000	Cu.ft/min
$(Q/S)_{Max}$	1.8	
$(Q/S)_{Min}$	1.5	
c	433.5	
F	0.92	
G	0.6248	
Z	0.95	
C	793.28927	
T_f	530	°R
m	0.2229992	
M	23754.595	

	DV P		
		P1	
		P2	
=	918	P3	DV
=		P4	
=		P5	
=	746	P6	DV

P2 UL	677	<=	1000
P3 UL	918	<=	1000
P4 UL	837	<=	1000
P5 UL	837	<=	1000
P6 UL	746	<=	754

P2 LL	677	>=	600
P3 LL	918	>=	600
P4 LL	837	>=	600
P5 LL	837	>=	600
P6 LL	746	>=	746

(Pa^2 - Pb^2) = ((Q*(L^0.5))/(D^2.667*C))^2	Eqn (2) H		Eqn (3) H
142920	1673	=	
142920	0	=	
142920			

Head 1	1673	>=	
Head 2	0	>=	0

Total Fuel Cost 1704329.2

Figure 3.2: User Interface of Excel Solver Add-in

3.8 Discussion of Results

The solution obtained through the proposed model is 1.704 x10^6, which is better than the solution to the problem discussed in Wu et al. (2000), which is 1.732 x10^6. In a well-designed network, the maximum pressure attained in the pipeline will be less than the MAOP and the maximum operating pressure of the compressors. Hence, the results of the proposed model and the model developed by Wu et al. (2000) are expected to be similar because in the numerical problem considered, the only difference between the two models is the MAOP constraint which is an upper bound for the pressure. Since the objective function value at the optimal condition is similar in both the model, the proposed model is validated.

It is observed that, in this model, if the inlet pressure and outlet pressure of the compressor are the same, then value of equation (1) will become zero. For flow of 13201 cubic feet per minute through a single compressor at an RPM of 5025, all the equations are satisfied. However, the value of fuel cost at the compressor station 2 is calculated to be zero. This means that the compressor is running at an RPM of 5025 without consuming any fuel, which is not possible.

The compressor running conditions are important and should be considered in calculating the fuel consumption of the compressor. However, in this model, Equation (1), the objective function is purely based on the pressure parameters and the compressor parameters were not considered. Hence, according to the model, even if the compressors run at a speed, but do not perform any adiabatic work (inlet and outlet pressures are the same), the fuel cost will be zero. However in reality, the compressor will be consuming fuel, while trying to do work even though the compressor running parameters is not significant enough to do work. Hence, this model does not hold true in cases where the inlet and outlet pressures of the compressor are equal.

3.9 Conclusion

The model discussed above takes into consideration only the fuel cost of the pipeline system. Also, the fuel cost equation does not hold true if the inlet pressure and outlet pressure are the same. In addition to the fuel cost, there are other costs involved in the pipeline operation system. These are not considered in the existing research. Therefore, a new model for the end-to-end pipeline system optimization through the selection of compressors based on horsepower requirement, capital cost, maintenance cost, pipeline dimensional specification and capital cost is proposed in the next chapter.

CHAPTER 4

NATURAL GAS PIPELINE NETWORK OPTIMIZATION

In this chapter, the second research objective of this research which involves the development of an optimization model that can be used to minimize the entire pipeline network cost is presented. The decision variables to be considered, the assumptions used to formulate the model as a mixed integer non-linear program (MINLP), the parameters involved as well as the constraints that must be considered to formulate the model is discussed in detail. A schematic representation of a pipeline network is shown in Figure 4.1.

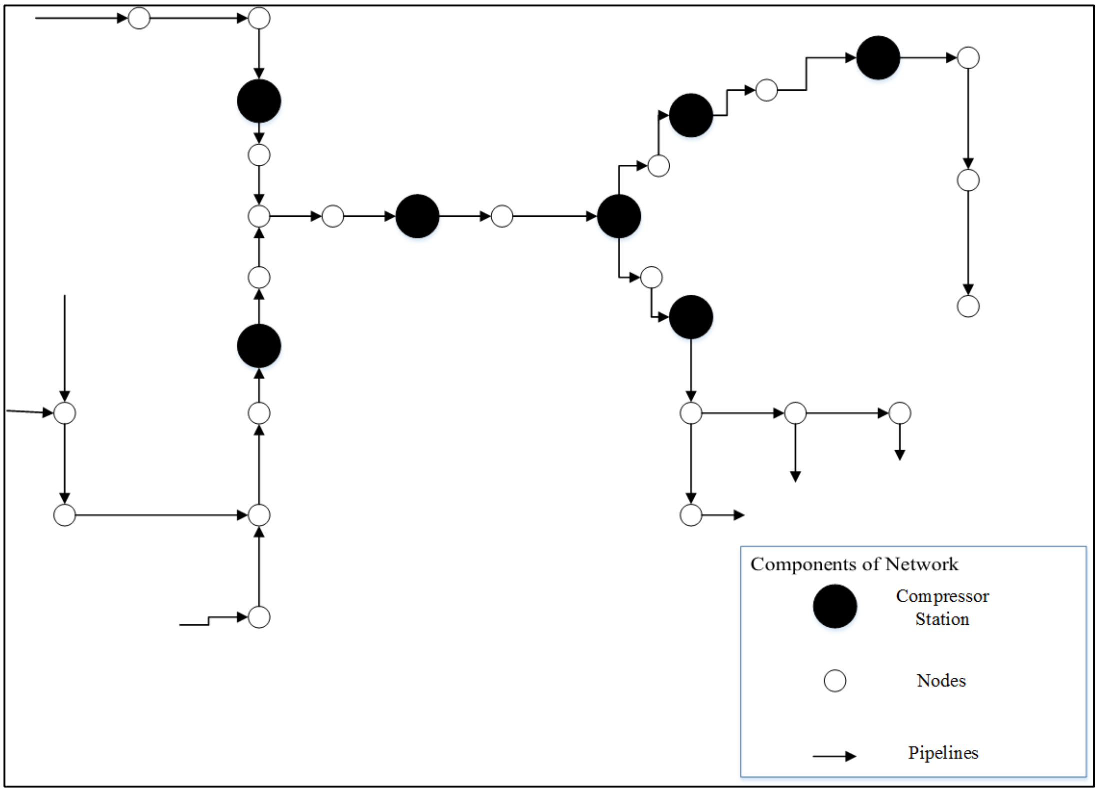


Figure 4.1: Schematic Representation of a Pipeline Network

4.1 Decision Variables

The factors that affect the pipeline network cost are the number of compressors for each configuration of horsepower rating, location of compressor station, pipeline inner diameter and thickness and the inlet pressure. The decision variables for a network with ‘n’ nodes, ‘k’ types of compressors (based on horsepower rating), and ‘a’ pipelines are shown below.

RP_n = Inlet pressure at receiving node ‘n’ (psig)

D_p = Inner Diameter of Pipeline (inch)

L_{an} = Length of pipeline ‘a’/distance between nodes ‘n’ and ‘n+1’ (miles)

B_{njk} = Binary variable for Compressor selection

B_{njk} = 1 if Compressor ‘j’ of type ‘k’ at node ‘n’ is selected

B_{njk} = 0 if Compressor ‘j’ of type ‘k’ at node ‘n’ is not selected

If the network has contracted pressure, then ‘RP_n’ will no longer be a decision variable since it becomes a constraint. Similarly, if the pipeline is already laid, then ‘D_p’ and ‘L_{an}’ will no longer be decision variables since they will become parameters.

4.2 Assumptions

A number of assumptions have to be made in order to be able to formulate this model as a MINLP. These are:

- All the compressors in a given station take in gas at a constant pressure, compress and push the gas out at a constant pressure.

- The operating condition of the Natural Gas Transmission system is assumed to be in steady state and isothermal.
- The compressibility and specific heat of the Natural Gas is assumed to be constant.
- At the end of the pipeline project operation, the resale value of assets is considered to be zero.
- The diameter and thickness of the pipeline is assumed to be constant throughout the network.

4.3 Objective Function

There are various costs associated with the operation of a Natural Gas transmission system and the objective function is the minimization of the total cost. For optimization purposes, only the most crucial costs associated with the pipeline system operations are considered in our model. They are listed below.

CC_k = Capital cost of a compressor unit of type ‘k’

MC_k = Annual maintenance cost of a compressor unit of type ‘k’

FC_k = Fuel cost of a compressor unit of type ‘k’ per HP-Hour

PC = Cost per mile of pipeline of inner diameter ‘D_p’ and thickness ‘t_p’. This can be calculated as follows.

Let Concrete Density = ‘SG’, Cost per pound of concrete = ‘C’. Then, the weight of the pipeline for a given inner diameter ‘D_p’ and thickness ‘t_p’ can be calculated using the standard mathematic formula used to find the weight of a hollow cylinder. This is given by the following equation, where 63360 is the factor to convert miles to inches.

$$PC = 0.785 \text{ x } ((D_P+t_p)^2 - D_P^2) \text{ x } 63360 \text{ x } SG \text{ x } C \rightarrow (19)$$

The other major costs in a pipeline operation are the capital cost of support equipment and maintenance and inspection cost of pipelines. The cost of inspection and maintenance of the pipeline is a major cost involved in the operation cost of the Natural Gas pipeline system because of regulations and cost to maintain the pipelines. The Pipeline and Hazardous Materials Safety Administration (PHMSA) published an Advanced Notice of Proposed Rulemaking (ANOPR) titled “Pipeline Safety: Safety of Gas Transmission Pipelines”, through which PHMSA is considering expanding the definition of a High Consequence Area (HCA), so that more miles of pipelines may become subject to integrity management requirements which regulates the inspection policies of the gas transmission pipelines (U.S.A Federal Energy Regulation Committee, 2014). Since the number of supporting equipment and the number of inspection points are proportionate to the length of pipeline, the cost associated with them is also proportionate to the length of pipeline. Since the cost associated with the length of pipeline is already considered, the capital cost of support equipment and maintenance and inspection cost of pipelines have been ignored in this model. The mathematical form of the objective function which is to be minimized, is given by (20) as shown below.

$$Z = \sum B_{njk} \text{ x } Y \text{ x } [MC_k + (FC_k \text{ x } 8760)] + [\sum L_{an} \text{ x } PC] + CC_k \quad \forall \text{ (n,j,k)} \rightarrow \qquad (20)$$

Where, ‘Y’ is the number of years for which the pipeline project will function and 8760 is the number of hours in a year.

A mixed integer nonlinear program (MINLP) model can be used for selecting the optimal values of the decision variables in order to get the overall minimum Natural Gas pipeline transportation operations cost.

If an existing Natural Gas transportation network is considered, the pipe design factors - 'D_p', 'L_{an}' and the capital cost of the compressors 'CC_k' will not be decision variables, since the network already exists. In this case, this model is reduced to identify the optimal values for only the compressor factors 'B_{njk}', and the objective function to be minimized is modified as shown below

$$Z = \sum B_{njk} \text{ x } [MC_k + (FC_k \text{ x } 8760)] \qquad \forall\ (n,j,k) \rightarrow \qquad (21)$$

4.4 Pipeline Network Parameters

The various parameters involved in the pipeline network design can be broadly classified as pipeline parameters, pressure parameters, gas flow parameters and compressor parameters. They are shown in Table 4.1, Table 4.2, Table 4.3 and Table 4.4, respectively.

Table 4.1: Pipeline Parameters

Parameters	**Notation**
Minimum available inner diameter of pipeline (inch)	$Dmin_p$
Maximum available inner diameter of pipeline (inch)	$Dmax_p$
Minimum available wall thickness of the pipeline (inch)	$tmin_p$
Maximum available wall thickness of the pipeline (inch)	$tmax_p$
Specified minimum yield strength	S

Table 4.2: Pressure Parameters

Parameters	**Notation**
Inlet pressure for pipeline ‘a’ / node ‘n’ (psig)	IP_n
Outlet pressure for pipeline ‘a’/ node ‘n+1’ (psig). This is also the resultant output pressure of a non-compressor node	OP_n
Inlet pressure at compressor node ‘n’ (psig)	CIP_n
Outlet pressure at compressor node ‘n’ (psig). This is also the resultant output pressure of compressor node	COP_n
Resultant output pressure of node ‘n’ (psig)	ROP_n
Minimum operation pressure of compressor of type ‘k’ (psig)	$Pmin_k$
Maximum operation pressure of compressor of type ‘k’ (psig)	$Pmax_k$
Minimum pressure recommended in the pipeline system (psig)	$Pmin_p$
Maximum pressure recommended in the pipeline system (psig)	$Pmax_p$
Maximum pressure attained in the pipeline system (psig)	OPmax
Contracted Pressure at node ‘n’ (psig)	$CONP_n$

Table 4.3: Gas Flow Parameters

Parameters	**Notation**
Volumetric flow rate (scf/D)	Q
Pipeline efficiency, a decimal value less than or equal to 1	E
Gas Gravity	G
Compressibility factor	Z
Base pressure (psig)	P_b
Base temperature, ºR (460 + ºF)	T_b
Average flow temperature, ºR (460 + ºF)	T_f

Table 4.4: Compressor Parameters

Parameters	**Notation**
HP rating of compressor 'j' of type 'k', at node 'n' (HP)	HP_{njk}
Total number of compressor of type 'k', that can be at node 'n'	N_{nk}

4.5 Constraints

A number of constraints must be included in the optimization model to cover the different criteria to be satisfied. These include flow criteria, brake horsepower requirement, pipe thickness, pipe pressure criteria, pipe diameter criteria, resultant pressure constraint and compressor constraints. Each of these is described in detail in the sections below.

4.5.1 Flow Equation

Two types of flow equations namely Weymouth Equation and General Flow Equation were discussed in Section 3.5. The Panhandle A Equation is a flow equation that is recommended for Natural Gas pipelines (Jusoh, 2010; Menon & Menon, 2013). The flow of Natural Gas in the pipeline is usually turbulent, and as the Panhandle A Equation is designed for such situations, it is suitable for Natural Gas pipeline operations. The Panhandle A Equation considering the elevation is given by (22A) and when the elevation is not considered, it is given by (22B).

$$Q_n = 435.87 \text{ x } E \text{ x } \left(\frac{\mathbf{T_b}}{\mathbf{P}_b}\right)^{1.0788} \text{ x } \left(\frac{\mathbf{IP_{ni}}^2 - e^s\mathbf{OP_{no}}^2}{\mathbf{G}^{0.8539} * \mathbf{T}_f * \mathbf{L}_{an} * Z}\right)^{0.5394} * D^{2.6182} \rightarrow \qquad (22A)$$

$$Q_n = 435.87 \text{ x } E \text{ x } \left(\frac{\mathbf{T_b}}{\mathbf{P}_b}\right)^{1.0788} \text{ x } \left(\frac{\mathbf{IP_{ni}}^2 - \mathbf{OP_{no}}^2}{\mathbf{G}^{0.8539} * \mathbf{T}_f * \mathbf{L}_{an} * Z}\right)^{0.5394} * D^{2.6182} \rightarrow \qquad (22B)$$

Where, 'E' is the pipeline efficiency, a decimal value less than 1.0.

4.5.2 Brake Horsepower Requirement

The following equation is used to calculate the brake horsepower requirement to pressurize gas from pressure CIP_n to COP_n (Menon et al., 2013).

$$\mathrm{BHP} = 0.0857 \text{ x } \frac{\mathbf{K}}{\mathbf{K-1}} \text{ x } Q_n \text{ x } T_f \text{ x } \left(\frac{Z}{\eta_a}\right) \text{ x } \left(\left(\frac{\mathbf{COP_n}}{\mathbf{CIP_n}}\right)^{\left(\frac{\mathbf{K-1}}{\mathbf{K}}\right)} - 1\right) \rightarrow \qquad (23)$$

Where, 'η_a' is adiabatic efficiency and 'K' is the specific heat of Natural Gas.

The actual horsepower required is calculated by multiplying the brake horsepower calculated above by the mechanical efficiency η_m. This is because Brake Horsepower = $\left(\frac{\mathrm{HP}}{\eta_m}\right)$ (Menon et al., 2013).

Therefore the actual horsepower required to increase the gas pressure from CIP_n to COP_n will be given by (24),

$$\mathrm{HP} = 0.0857 \text{ x } \frac{\mathbf{K}}{\mathbf{K-1}} \text{ x } Q_n \text{ x } T_f \text{ x } \left(\frac{Z}{\eta_a}\right) \text{ x } \left(\left(\frac{\mathbf{COP_n}}{\mathbf{CIP_n}}\right)^{\left(\frac{\mathbf{K-1}}{\mathbf{K}}\right)} - 1\right) \text{ x } \eta_m \rightarrow \qquad (24)$$

From equation (24), the value of COP_n can be calculated. For simplicity, let $\left(\frac{\mathbf{K-1}}{\mathbf{K}}\right)$ be represented by 'm'

$$P_{cno} = \left[\left(\mathrm{M} * \left(\frac{\mathrm{HP}}{Q}\right)\right) + 1\right]^{\left(\frac{1}{\mathrm{m}}\right)} \text{ x } P_{cni} \rightarrow \qquad (25)$$

Where,

$$\mathrm{M} = \left(\frac{\mathrm{m} * \eta_{\mathbf{a}}}{\eta_{\mathbf{m}} * 0.0857 * Z * \mathrm{T}_{\mathbf{f}}}\right)$$

4.5.3 Pipeline Thickness

To calculate the thickness of the pipeline, it is important to know the Maximum Allowable Operating Pressure (MAOP). In this model, the maximum pressure that occurs in the pipeline to have the optimal objective function value is considered as MAOP. The thickness can be calculated from MAOP by using the equation below (Menon et al., 2013).

$$t_p = \frac{\mathrm{MAOP} * (D_p + 2t_p)}{2 * S * F_1 * F_2 * F_3} \quad \rightarrow \quad (26)$$

The above equation can be simplified as

$$t_p = \frac{\mathrm{MAOP} * D_p}{2 * ((S * F_1 * F_2 * F_3) - \mathrm{MAOP})} \quad \rightarrow \quad (27)$$

Where,

F_1 = Seam joint factor. 1.0 for seamless and submerged arc welded pipes

F_2 = Design factor. 0.72 for interstate pipelines. However, it can be as low as 0.4 depending upon class location and type of construction

F_3 = Temperature deration factor. 1.00 for below 250ºF (709ºR)

4.5.4 Pipe Pressure Constraint

The pressure in the pipeline should be between the lower limit and upper limit of interstate pipeline design guidelines and it should also be less than or equal to the MAOP. This is given by the following equations.

$$\mathrm{Pmin}_p \leq \mathrm{IP}_n \leq \mathrm{Pmax}_p \qquad \forall\,(n) \quad \rightarrow \quad (28)$$

$$Pmin_p \leq OP_n \leq Pmax_p \qquad \forall (n) \rightarrow \qquad (29)$$

$$IP_n \leq MAOP \qquad \forall (n) \rightarrow \qquad (30)$$

$$OP_n \leq MAOP \qquad \forall (n) \rightarrow \qquad (31)$$

Also, the maximum pressure that is attained in the pipeline system is considered as the MAOP.

$$OPmax = MAOP \qquad \rightarrow \qquad (32)$$

4.5.5 Pipe Dimension Constraints

The pipeline has dimensional constraints on the minimum and maximum inner diameter and thickness based on interstate design guidelines and standard sizes that exist in the market. They are shown in the following constraints.

$$Dmin_p \leq D_p \leq Dmax_p \qquad \rightarrow \qquad (33)$$

$$tmin_p \leq t_p \leq tmax_p \qquad \rightarrow \qquad (34)$$

4.5.6 Resultant Pressure Constraints

The resultant pressure constraints are required to ensure that the outlet pressure is greater than or equal to the contracted pressure and it is also the inlet pressure for the next node. When the pressure is greater than the contracted pressure, at the point of delivery, pressure control valves are used to reduce the pressure to the contracted pressure.

$$ROP_n \geq CONP_n \qquad \forall (n) \rightarrow \qquad (35)$$

$$ROP_{(n-1)} = IP_n \qquad \forall (n) \rightarrow \qquad (36)$$

4.5.7 Compressor Constraints

The compressor can operate only between a certain pressure ranges. Also, the total number of compressors selected should be less than the number of compressors available/can be procured. Finally, the sum of the length of the pipelines/distance between the nodes, should be equal to the distance between the receiving node and the outlet node. They are shown below.

$$Pmin_k \leq CIP_n \leq Pmax_k \qquad \forall (k) \rightarrow \qquad (37)$$

$$Pmin_k \leq COP_n \leq Pmax_k \qquad \forall (k) \rightarrow \qquad (38)$$

$$\sum_{n=0}^{N} B_{njk} \leq N_{nk} \qquad \rightarrow \qquad (39)$$

$$\sum_{n=0}^{N} L_{an} = L_N \qquad \rightarrow \qquad (40)$$

Where, L_N is the distance between the inlet node and the N^{th} outlet node

4.5.8 Non-Negativity & Integer Constraints

The length of the pipeline and the inlet pressure cannot be negative and hence, non-negativity constraints should be included for the inlet pressure and the pipeline length. They are shown below.

$$L_{an} \geq 0 \qquad \forall (n) \rightarrow \qquad (41)$$

$$RP_n \geq 0 \qquad \forall (n) \rightarrow \qquad (42)$$

$$RP_n = \text{Integer} \qquad \forall (n) \rightarrow \qquad (43)$$

$$D_p = \text{Integer} \qquad \rightarrow \qquad (44)$$

4.6 Mathematical Model

The mathematical model developed is a mixed integer nonlinear program. The model is shown below. The objective function is:

$$\text{Minimize } Z = \sum B_{njk} \text{ x } Y \text{ x } [MC_k + (FC_k \text{ x } 8760)] + [\sum L_{an} \text{ x } PC] + CC_k \qquad \forall (n,j,k)$$

Subject to:

$$Q_n = 435.87 \text{ x } E \text{ x } \left(\frac{\mathbf{T_b}}{\mathbf{P}_b}\right)^{1.0788} \text{ x } \left(\frac{\mathbf{IP_{ni}}^2 - e^s\mathbf{OP_{no}}^2}{\mathbf{G}^{0.8539} * \mathbf{T}_f * \mathbf{L}_{an} * Z}\right)^{0.5394} * D^{2.6182}$$

$$HP = 0.0857 \text{ x } \frac{\mathbf{K}}{\mathbf{K-1}} \text{ x } Q_n \text{ x } T_f \text{ x } \left(\frac{Z}{\eta_a}\right) \text{ x } \left(\left(\frac{\mathbf{COP_n}}{\mathbf{CIP_n}}\right)^{\left(\frac{\mathbf{K-1}}{\mathbf{K}}\right)} - 1\right) \text{ x } \eta_m$$

$$t_p = \frac{MAOP * (D_{\mathbf{p}} + 2t_{\mathbf{p}})}{2 * S * F_{\mathbf{1}} * F_{\mathbf{2}} * F_{\mathbf{3}}}$$

$Pmin_p \leq IP_n \leq Pmax_p$ $\qquad \forall$ (n)

$Pmin_p \leq OP_n \leq Pmax_p$ $\qquad \forall$ (n)

$IP_n \leq MAOP$ $\qquad \forall$ (n)

$OP_n \leq MAOP$ $\qquad \forall$ (n)

$OPmax = MAOP$

$Dmin_p \leq D_p \leq Dmax_p$

$tmin_p \leq t_p \leq tmax_p$

$ROP_n \geq CONP_n$ $\qquad \forall$ (n)

$ROP_{(n-1)} = IP_n$ $\qquad \forall$ (n)

$Pmin_k \leq \quad CIP_n \leq \quad Pmax_k \qquad \forall (k)$

$Pmin_k \leq \quad COP_n \leq \quad Pmax_k \qquad \forall (k)$

$\sum_{n=0}^{N} B_{njk} \leq N_{nk}$

$\sum_{n=0}^{N} L_{an} = L_N$

B_{njk} = Binary variable for Compressor selection

B_{njk} = 1 if Compressor ‘j’ of type ‘k’ at node ‘n’ is selected

B_{njk} = 0 if Compressor ‘j’ of type ‘k’ at node ‘n’ is not selected

$L_{an} \geq 0 \qquad \forall (n)$

$RP_n \geq 0 \qquad \forall (n)$

RP_n = Integer $\qquad \forall (n)$

D_p = Integer

4.7 Solving the Optimization Model

In order to evaluate the possibility of finding optimal solutions efficiently, metaheuristic techniques will be applied. Since OptQuest is the most commonly used optimization engine in simulation software (example: Arena and Simul8), the use of which is becoming a growing practice (Romo et al., 2009), and Genetic Algorithms is one of the most widely used metaheuristic algorithms for solving complex optimization problems including Natural Gas transportation problems (Goldberg, 1987; Sanaye & Mahmoudimehr, 2012), OptQuest and Genetic Algorithm were selected.

4.7.1 Genetic Algorithm

Traditional heuristic optimization methods have two drawbacks – they are mostly local search algorithms and they are rigid (Goldberg, 1987). Genetic Algorithms have no such restrictions.

Genetic Algorithms (GA) are canonical global search stochastic and improvement algorithms which work on the principle of natural genetics. The Darwinian survival of fittest combined with a randomized yet structured data exchange between crossing chromosomes (solution sets) works in the GA. After every crossover, a new generation of chromosomes are formed using sections of the fittest of the parent/previous generation chromosomes. Even though GA is stochastic, the search procedure is efficiently and carefully guided with the help of historic data (Goldberg, 1989).The characteristics of GA are discussed below (Goldberg, 1989).

- Initial Population: These are random set of initial solutions for the problem.
- Chromosomes: These are the individuals in the population.
- Genes: Every chromosome has a set of genes (individual values of decision variables) in a chromosome.
- Generations: The chromosomes evolve through successive generations.
- Fitness: Each chromosome will have a fitness factor (objective function value) associated with it. Evolution will depend the value of the fitness function.
- Offspring: New chromosomes are formed from the preceding generations. In order to achieve this, two types of operators are required.
    - Genetic Operators : Crossover and mutation
    - Evolutionary Operators.

- Termination: The condition to stop the evolution, in the GA. Some of the examples of the termination condition are number of generations and rate of change in fitness function value.

Sequential steps followed during the application of GA and the iterative procedure is shown in Figure 4.2.

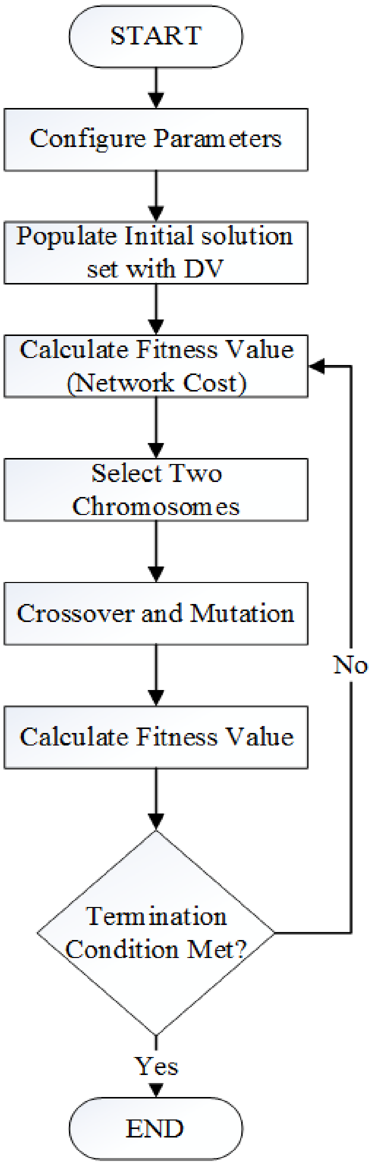


Figure 4.2: Iterative Algorithm Applied in GA

The special features of GA are listed below.

- GA works with the coding of the solution, not the solution itself.
- GA uses the fitness function to improve solution. The derivatives are not used.
- GA can be used to solve any type of problem (linear/non-linear)
- GA can be used to perform both exploration and exploitation of the solution space.
    - Exploration: Process of finding the region which is having the optimal solution
    - Exploitation: Process of searching the explored region to find the optimal solution.

Figure 4.3 shows an example of the chromosome set used in the model explained in this chapter.

Pipeline Design Variable		Length of Pipeline/Distance between Nodes				Compressor Selection at Node 1						Compressor Selection at Node 2							Compressor Selection at Node n					
RP_n	Dp	L_{a1}	L_{a2}	....	L_{an}	B_{111}	B_{112}	....	B_{11k}	....	B_{1jk}	B_{211}	B_{212}	....	B_{21k}	....	B_{2jk}	....	B_{n11}	B_{n12}	....	B_{n1k}	....	B_{njk}

Figure 4.3: Schematic Diagram of the Chromosome formation in GA

4.7.2 OptQuest

OptQuest is an optimization module that incorporates Scatter Search as primary search algorithm, Tabu Search as secondary and Neural Networks as the final method (Eskandari & Mahmoodi, 2011) to find the global optimal solution. Since this algorithm does not follow the ladder solution approach, it does not get stuck in the local optimal. Scatter Search is applied to generate a vector set of initial solutions. It then identifies the better solution in the available solution set and uses it as the reference solution. Then, this solution is used as the initial solution and apply the heuristic process repeatedly until the stopping conditions are met, as illustrated in Figure 4.4.

Tabu Search is used to ensure that the search does not reinvestigate the already achieved solution. A Neural Network is used to ensure that the possibly poor solutions are not evaluated in order to save time. The stopping condition of OptQuest is the same as in GA, a user specified maximum number of trails, percentage change in optimal value or time.

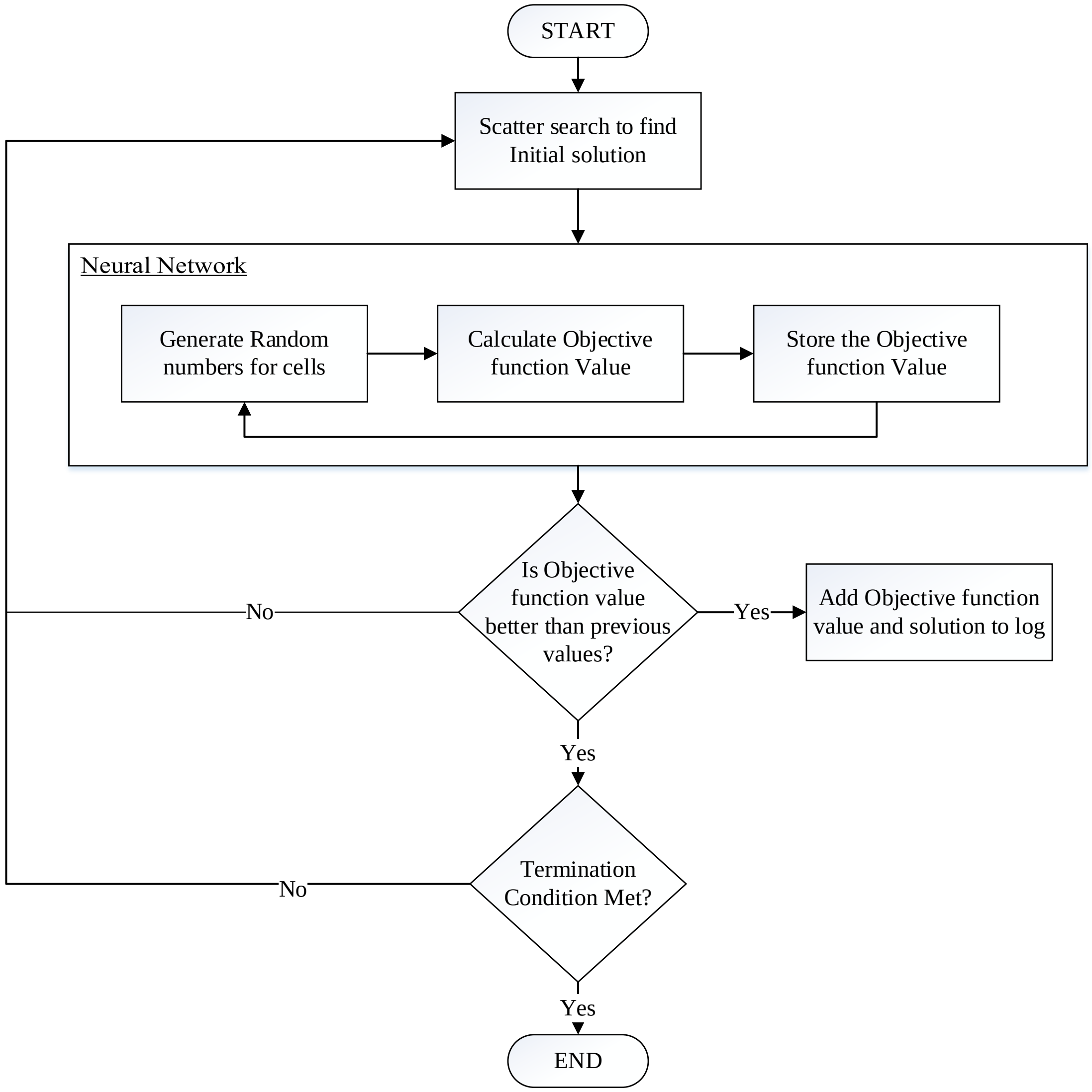


Figure 4.4: Working Principle of OptQuest

CHAPTER 5

CASE STUDY

This chapter demonstrates the application of a specific case of the proposed pipeline network cost minimization model on an existing real world Natural Gas transportation pipeline network, to find the optimal values for the decision variables and also identify the most suitable algorithm. The Natural Gas pipeline network of Gas Transmission Northwest LLC, a part of TransCanada Corporation is used as a case study. The problem is solved as three scenarios - Scenario 1 is the real world gas transmission network without considering pipeline elevation and Scenario 2 considers the pipeline elevation. This is done to show the importance of including pipeline elevation in the optimization models. Scenario 3 is more expansive and considers the diameter of the pipeline and location of the compressors as decision variables.

Also, Scenario 1 and Scenario 2 were solved using OptQuest and GA in the Evolver Excel add-in. The results of Scenario 1 and 2, through the two algorithms were compared to identify the most suitable algorithm for the proposed Natural Gas Transmission problem. Finally, Scenario 3 is solved using the algorithm which was found to be the better of the two algorithms.

5.1 Pipeline Network

The pipeline network of the Gas Transmission Network LLC, which runs between British Columbia and California is shown in Figure 5.1 (Federal Energy Regulatory Commission, 2014). The inner diameter of the pipeline is 48” (U.S Energy Information Administration, n.dc) and the total length of the pipeline is 612.46 miles. The pipeline originates at Kingsgate, British Columbia and has 12 compressor station locations (identified as station numbers 3 through 14 in Figure 13) and 31 compressor stations. The details of the compressor stations is shown Table 5.1.

Table 5.1: Compressor Station Locations and Installed Horsepower Capacity

Station #	**Location of Station**	**Mile point**	**Installed HP at Each Station**				**Total Installed HP**
			Station 1	**Station 2**	**Station 3**	**Station 4**	
3	Eastport	2.5	16500	35000			51500
4	Sandpoint	46.7	19500	15000	14100		48600
5	Athol	87.61	14300	35000			49300
6	Rosalia	143.5	14100	14210	19500		47800
7	Starbuck	212.5	14300	39700			54000
8	Wallula	255.6	19500	17800	14300		51600
9	Ione	319.5	14100	14100			28200
10	Kent	368.3	14100	14300	19500		47900
11	Madras	425.1	13000	12100			25100
12	Bend	472.8	16600	14300	19500	14300	64700
13	Chemult	529.5	19500	14300	14300		48100
14	Bonanza	599.2	14100	17500			31600

Figure 5.1: Map of Gas Transmission Northwest LLC Pipeline Network

5.2 Scenarios with RP_n, B_{njk} and D_p as Decision Variables

Since this is an existing network, the compressor station location, distance between nodes/length of pipeline, the diameter and thickness of pipeline are pre-determined and hence they are parameters and not decision variables. The decision variable in this specific case are the inlet pressure at the receiving node and the selection of compressors (binary). They are represented below.

RP_n = Inlet pressure at receiving node ‘n’ (psig)

B_{njk} = Binary variable for Compressor selection

  B_{njk} = 1 if Compressor ‘j’ of type ‘k’ at node ‘n’ is selected

  B_{njk} = 0 if Compressor ‘j’ of type ‘k’ at node ‘n’ is not selected

For the purpose of comparing the time taken to solve the scenarios, the inner diameter of the pipeline ‘D_p’ is also considered as a Decision Variable.

The objective function is to minimize the compressor maintenance cost and fuel cost by selecting the optimal combination of selection of compressors and pressures.

$$\text{Objective} = \text{Minimize} \sum B_{njk} \text{ x } [MC_k + (FC_k \text{ x } 8760)] \qquad \forall\ (n,j,k)$$

In this first application of MINLP model, two scenarios have been considered. These scenarios are listed below.

- Scenario 1: Real world network with RP_n, B_{njk} and D_p as decision variables with pipeline elevation difference ignored
- Scenario 2: Real world network with RP_n, B_{njk} and D_p as decision variables considering pipeline elevation differences.

The flow equation used in Scenario 1 is (22B) and that for the Scenario 2 is (22A).

5.2.1 Assumptions

The data related to the number of compressor units at each station are not publically available and hence they are assumed based on Natural Gas.org, (n.d) as displayed in Table 5.2.

Table 5.2: Number of Compressors at Each Station

Compressor Station #	**Location of Compressor Station**	**Total Installed HP**	**No. of Compressors at Each Station**				
			100 HP	**1500 HP**	**2000 HP**	**4500 HP**	**7500 HP**
3	Eastport	51500	0	1	4	1	5
4	Sandpoint	48600	1	6	4	2	3
5	Athol	49300	3	4	2	2	4
6	Rosalia	47800	3	1	2	6	2
7	Starbuck	54000	0	1	6	4	3
8	Wallula	51600	1	3	4	2	4
9	Ione	28200	2	8	2	1	1
10	Kent	47900	4	3	2	2	4
11	Madras	25100	1	1	2	1	2
12	Bend	64700	2	4	0	3	6
13	Chemult	48100	1	7	3	2	3
14	Bonanza	31600	1	5	6	1	1

There is no contract regarding the delivery pressure at any of the outlet nodes (Collins, 2014). Hence, the delivery pressure equality constraints are not applicable in this case. The fuel consumption in terms of Btu, for each of the compressor is assumed based on Eastern Research Group, (2006). Also the capital cost and annual maintenance cost for each of the compressor units has been assumed. The information is shown in Table 5.3.

Table 5.3: Compressor Capital, Maintenance and Fuel Consumption Cost

Compressor Costs	**100 HP**	**1500 HP**	**2000 HP**	**4500 HP**	**7500 HP**
Maintenance $/Year	8000	10000	12000	15000	17000
Fuel Cost $/HP-Hr	0.43	0.43	0.43	0.43	0.43
Fuel Consumption Btu/HP-Hr	8769	8580	8580	8583	8583
Capital Cost	$30,000	$200,000	$250,000	$300,000	$500,000

The fuel cost shown in Table 5.3 is calculated from the fuel consumption, energy equivalent of Natural Gas and cost of a gallon of Natural Gas. This is shown below.

Energy equivalent of Natural Gas = 20,160 Btu/Lb (Approx.)

1 Gallon of Natural Gas = 3.5 Lb (Approx.)

Cost of Natural Gas = $3.5/Gallon = $1/Lb (Approx.)

The operations parameter assumptions are listed in Table 5.4. The pressure parameters for the 'k' types of compressors are assumed to be the same.

Table 5.4: Operation Parameters

Parameter	**Notation**	**Value**
Maximum Operating Pressure of Compressors (psig)	$Pmax_k$	1500
Minimum Operating Pressure of Compressors (psig)	$Pmin_k$	600
Maximum Pressure in Pipeline (psig)	$Pmax_p$	1500
Minimum Pressure in Pipeline (psig)	$Pmin_p$	200
Maximum Allowable Operating Pressure (psig)	MAOP	1700
Pipeline Efficiency	E	0.92
Gas Gravity (Dimensionless)	G	0.6248
Compressibility Factor	Z	0.95
Base Pressure (psig)	P_b	14.73
Base Temperature °R	T_b	530
Adiabatic Efficiency of Compressor	η_a	0.75
Mechanical Efficiency of Compressor	η_m	0.95
Specific Heat of Natural Gas (Dimensionless)	K	1.287

To understand the effect of elevation on the decision variables and the objective function, the elevation for each node is assumed for consideration in Scenario 2. The assumed relative elevation is shown in Table 5.5.

Table 5.5: Scenario 2: Relative Elevation Considered Between Nodes

Station #	Nodes	Relative Elevation (feet)
-	Kingsgate (inlet)	0
3	Eastport	-10
4	Sandpoint	20
5	Athol	25
-	Spokane (Outlet)	-30
6	Rosalia	-40
-	Palouse (Outlet)	45
7	Starbuck	30
8	Wallula	35
-	Stanfield (Outlet)	-30
9	Ione	45
10	Kent	-20
12	Madras	5
13	Bend	10
14	Chemult	25
15	Bonanza	15
-	Klamath Falls (Output)	0
-	Tuscarora (Outlet)	0
-	Malin (outlet)	0

5.2.2 Solution of MINLP Model

The MINLP model was solved using OptQuest and GA in Microsoft Excel 2013 through Evolver add-in of Excel. The model was solved in a computer which had Intel Core i7 3.2 GHz processor and 8 GB RAM.

The termination condition used for OptQuest and GA is that the optimization will stop if the objective function value does not improve by more than 2% for 20000 consecutive generations.

The default setting for the GA is shown below.

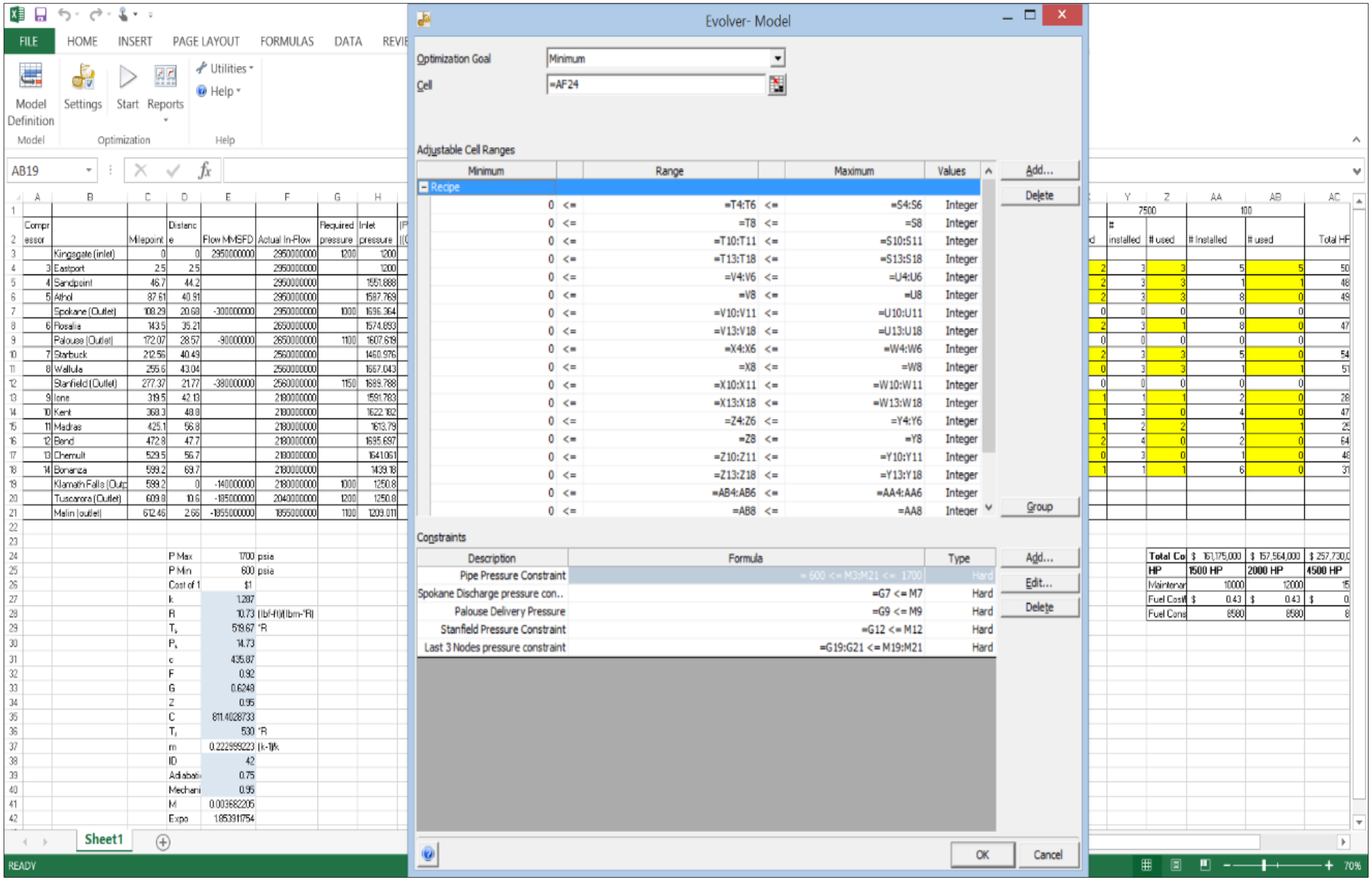
- Population Size = 50
- Crossover Rate = 0.5
- Mutation Rate = 0.1

The proposed model is solved using GA by considering all the available operators. It is also possible to manually select one or more operators that we believe will give the better solution. Evolver identifies which operator will best suit the model and at the end of the optimization, the Evolver Optimization summary describes the operators which had a high impact in getting the optimal solution. The total set of operators available in the Evolver GA are as follows (Palisade n.d).

- **Parent Selection:** The initial set of solutions that were found, which are the parents for the upcoming generations.
- **Standard Mutation:** In this mutation, the probability distribution of the new gene value is uniformly distributed across the entire allowable range.
- **Standard Crossover:** In this crossover, the formation of the child chromosomes happens by randomly swapping the parent genes.
- **Backtrack:** When Evolver tries each new value for the decision variables, it checks to see if all the constraints are satisfied and if they are not, it backtracks to the previous values that do meet the constraint.
- **Arithmetic crossover:** In this type of crossover, the child chromosomes are formed by taking the average of the parent genes, weighted by the default crossover rate.

- **Heuristic crossover:** In heuristic crossover, the child chromosomes are formed by linearly extrapolating the parent genes. The extrapolation is chosen based on the default crossover rate.
- **Cauchy Mutation:** In this mutation, the distribution of the gene value is like a Cauchy function, centered at the current value, with the width depended on the proximity of the current value to the allowable range boundary.
- **Boundary Mutation:** This operator mutates the genes to the boundary of the allowable range.
- **Non-Uniform Mutation:** This operator ensures that at the initial mutations are uniformly distributed across the entire allowable range of the gene and in later mutations, the width of distribution is reduced, thus confining the mutation more locally around the current value of the genes.
- **Local Search:** Local Search operator ensures that the new solutions generated are short, local search on the existing population. Crossover is ignored. The size of the search is dynamically adjusted based on the nature of the model.

The model and user interface of GA of Evolver with operators used, for the Natural Gas network cost minimization model is shown in Figure 5.2 and Figure 5.3, respectively.



	A	B	C	D	E	F	G	H
1								
2	Compressor		Milepoint	Distance	Flow MMSFD	Actual In-Flow	Required pressure	Inlet pressure
3		Kingsgate (inlet)	0	0	2950000000	2950000000	1200	1200
4	3	Eastport	2.5	2.5		2950000000		1200
5	4	Sandpoint	46.7	44.2		2950000000		1551.888
6	5	Athol	87.61	40.91		2950000000		1587.769
7		Spokane (Outlet)	108.29	20.68	-300000000	2950000000	1000	1696.364
8	6	Rosalia	143.5	35.21		2650000000		1574.893
9		Palouse (Outlet)	172.07	28.57	-90000000	2650000000	1100	1607.619
10	7	Starbuck	212.56	40.49		2560000000		1460.976
11	8	Wallula	255.6	43.04		2560000000		1667.043
12		Stanfield (Outlet)	277.37	21.77	-380000000	2560000000	1150	1689.788
13	9	Ione	319.5	42.13		2180000000		1591.783
14	10	Kent	368.3	48.8		2180000000		1622.182
15	11	Madras	425.1	56.8		2180000000		1613.79
16	12	Bend	472.8	47.7		2180000000		1695.697
17	13	Chemult	529.5	56.7		2180000000		1641.061
18	14	Bonanza	599.2	69.7		2180000000		1439.18
19		Klamath Falls (Outp	599.2	0	-140000000	2180000000	1000	1250.8
20		Tuscarora (Outlet)	609.8	10.6	-185000000	2040000000	1200	1250.8
21		Malin (outlet)	612.46	2.66	-1855000000	1855000000	1100	1209.011

	D	E	F
24	P Max	1700	psia
25	P Min	600	psia
26	Cost of 1	$1	
27	k	1.287	
28	R	10.73	(lbf-ft)/(lbm-°R)
29	T_b	519.67	°R
30	P_b	14.73	
31	c	435.87	
32	F	0.92	
33	G	0.6248	
34	Z	0.95	
35	C	811.4028733	
36	T_1	530	°R
37	m	0.222999223	(k-1)/k
38	ID	42	
39	Adiabati	0.75	
40	Mechani	0.95	
41	M	0.003682205	
42	Expo	1.853911754	

Evolver- Model

Optimization Goal: Minimum

Cell: =AF24

Adjustable Cell Ranges

Minimum		Range		Maximum	Values
Recipe					
0	<=	=T4:T6	<=	=S4:S6	Integer
0	<=	=T8	<=	=S8	Integer
0	<=	=T10:T11	<=	=S10:S11	Integer
0	<=	=T13:T18	<=	=S13:S18	Integer
0	<=	=V4:V6	<=	=U4:U6	Integer
0	<=	=V8	<=	=U8	Integer
0	<=	=V10:V11	<=	=U10:U11	Integer
0	<=	=V13:V18	<=	=U13:U18	Integer
0	<=	=X4:X6	<=	=W4:W6	Integer
0	<=	=X8	<=	=W8	Integer
0	<=	=X10:X11	<=	=W10:W11	Integer
0	<=	=X13:X18	<=	=W13:W18	Integer
0	<=	=Z4:Z6	<=	=Y4:Y6	Integer
0	<=	=Z8	<=	=Y8	Integer
0	<=	=Z10:Z11	<=	=Y10:Y11	Integer
0	<=	=Z13:Z18	<=	=Y13:Y18	Integer
0	<=	=AB4:AB6	<=	=AA4:AA6	Integer
0	<=	=AB8	<=	=AA8	Integer

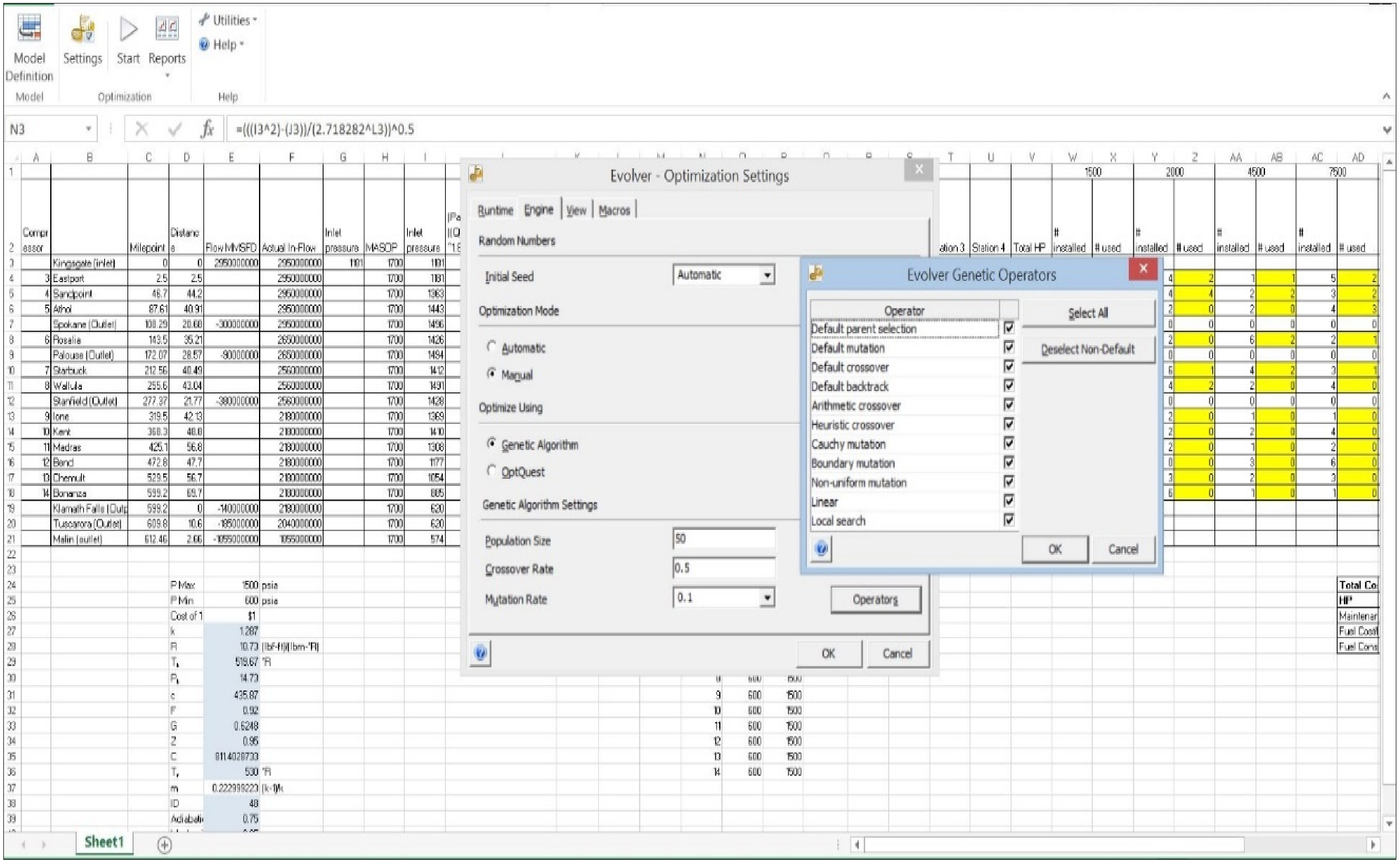
Constraints

Description	Formula	Type
Pipe Pressure Constraint	= 600 <= M3:M21 <= 1700	Hard
Spokane Discharge pressure con..	=G7 <= M7	Hard
Palouse Delivery Pressure	=G9 <= M9	Hard
Stanfield Pressure Constraint	=G12 <= M12	Hard
Last 3 Nodes pressure constraint	=G19:G21 <= M19:M21	Hard

X	Y	Z	AA	AB	AC
	7500		100		
d	# installed	# used	# Installed	# used	Total HF
2	3	3	5	5	50
2	3	3	1	1	48
2	3	3	8	0	49
0	0	0	0	0	
2	3	1	8	0	47
0	0	0	0	0	
2	3	3	5	0	54
0	3	3	1	1	51
0	0	0	0	0	
1	1	1	2	0	28
1	3	0	4	0	47
1	2	2	1	1	25
2	4	0	2	0	64
0	3	0	1	0	46
1	1	1	6	0	31

Z	AA	AB	AC
Total Co	$ 161,175,000	$ 157,564,000	$ 257,730,(
HP	1500 HP	2000 HP	4500 HP
Maintenar	10000	12000	15
Fuel Cos	$ 0.43	$ 0.43	$ 0
Fuel Cons	8580	8580	8

Figure 5.2: Natural Gas Network Cost Minimization Model



N3 =(((I3^2)-(J3))/(2.718282^L3))^0.5

	A	B	C	D	E	F	G	H	I
2	Compressor		Milepoint	Distance	Flow MMSFD	Actual In-Flow	Inlet pressure	MASOP	Inlet pressure
3		Kingsgate (inlet)	0	0	2950000000	2950000000	1181	1700	1181
4	3	Eastport	2.5	2.5		2950000000		1700	1181
5	4	Sandpoint	46.7	44.2		2950000000		1700	1363
6	5	Athol	87.61	40.91		2950000000		1700	1443
7		Spokane (Outlet)	108.29	20.68	-300000000	2950000000		1700	1496
8	6	Rosalia	143.5	35.21		2650000000		1700	1426
9		Palouse (Outlet)	172.07	28.57	-90000000	2650000000		1700	1494
10	7	Starbuck	212.56	40.49		2560000000		1700	1412
11	8	Wallula	255.6	43.04		2560000000		1700	1491
12		Stanfield (Outlet)	277.37	21.77	-380000000	2560000000		1700	1428
13	9	Ione	319.5	42.13		2180000000		1700	1369
14	10	Kent	368.3	48.8		2180000000		1700	1410
15	11	Madras	425.1	56.8		2180000000		1700	1308
16	12	Bend	472.8	47.7		2180000000		1700	1177
17	13	Chemult	529.5	56.7		2180000000		1700	1054
18	14	Bonanza	599.2	69.7		2180000000		1700	885
19		Klamath Falls (Outp	599.2	0	-140000000	2180000000		1700	620
20		Tuscarora (Outlet)	609.8	10.6	-185000000	2040000000		1700	620
21		Malin (outlet)	612.46	2.66	-1055000000	1055000000		1700	574

	D	E	F
24	P Max	1500	psia
25	P Min	600	psia
26	Cost of 1	$1	
27	k	1.287	
28	R	10.73	(lbf-ft)/(lbm-°R)
29	T_b	519.67	°R
30	P_b	14.73	
31	c	435.87	
32	F	0.92	
33	G	0.6248	
34	Z	0.95	
35	C	811.4028733	
36	T_f	530	°R
37	m	0.222999223	(k-1)/k
38	ID	48	
39	Adiabati	0.75	

Evolver - Optimization Settings

Runtime | Engine | View | Macros

Random Numbers

Initial Seed: Automatic

Optimization Mode

○ Automatic
● Manual

Optimize Using

● Genetic Algorithm
○ OptQuest

Genetic Algorithm Settings

Population Size: 50

Crossover Rate: 0.5

Mutation Rate: 0.1

Evolver Genetic Operators

Operator	
Default parent selection	☑
Default mutation	☑
Default crossover	☑
Default backtrack	☑
Arithmetic crossover	☑
Heuristic crossover	☑
Cauchy mutation	☑
Boundary mutation	☑
Non-uniform mutation	☑
Linear	☑
Local search	☑

Figure 5.3: User Interface of GA of Evolver showing the Operators Used

5.2.3 Results

Results for Scenario 1:

The optimization model for Scenario 1 was executed in two different algorithms – Excel Evolver: GA and Excel Evolver: OptQuest. The values of the results are compared in section 5.3. The best result was given by GA, where the objective function was found to be $485 Million. The value of D_p was found to be 48”, which is the actual dimension of the existing network. The result is shown in Table 5.6 and Table 5.7. Table 5.6 shows the compressor units selected and Table 5.7 shows the pressure at each node.

Table 5.6: Results of Scenario 1: Compressor Units

Selected Station #	**Node**	**Total Selected HP**	**No. of Compressors Selected**				
			100 HP	**1500 HP**	**2000 HP**	**4500 HP**	**7500 HP**
3	Eastport	25000		1	2	1	2
4	Sandpoint	32000		3	4	1	2
5	Athol	24000		1			3
6	Rosalia	18000		1		2	1
7	Starbuck	20000		1	1	2	1
8	Wallula	4000			2		
9	Ione	12500		7	1		

A comparison of the total installed HP in the existing network vs. the selected HP through the optimization is shown in Table 5.8. Also, the comparison of compressors installed vs. the compressors selected is shown in Figure 5.4.

Table 5.7: Results of Scenario 1: Inlet and Outlet Pressure at each Nodes

Station #	Node	Pipeline Inlet Pressure	Pipeline Outlet/ Station Inlet Pressure	Station Outlet Pressure
-	Kingsgate	1181	1181	1181
3	Eastport	1181	1170	1363
4	Sandpoint	1363	1189	1444
5	Athol	1444	1294	1498
-	Spokane	1498	1427	1427
6	Rosalia	1427	1321	1493
-	Palouse	1493	1412	1412
7	Starbuck	1412	1297	1493
8	Wallula	1493	1377	1417
-	Stanfield	1417	1356	1356
9	Ione	1356	1264	1402
10	Kent	1402	1298	1298
11	Madras	1298	1166	1166
12	Bend	1166	1042	1042
13	Chemult	1042	872	872
14	Bonanza	872	600	600
-	Klamath Falls	600	600	600
-	Tuscarora	600	554	554
-	Malin	554	544	544

Table 5.8: HP Installed Vs. HP Selected for Scenario 1

Station #	Installed HP	Selected HP
3	51500	25000
4	48600	32000
5	49300	24000
6	47800	18000
7	54000	20000
8	51600	4000
9	28200	12500
10	47900	
11	25100	
12	64700	
13	48100	
14	31600	
Total	**548400**	**135500**

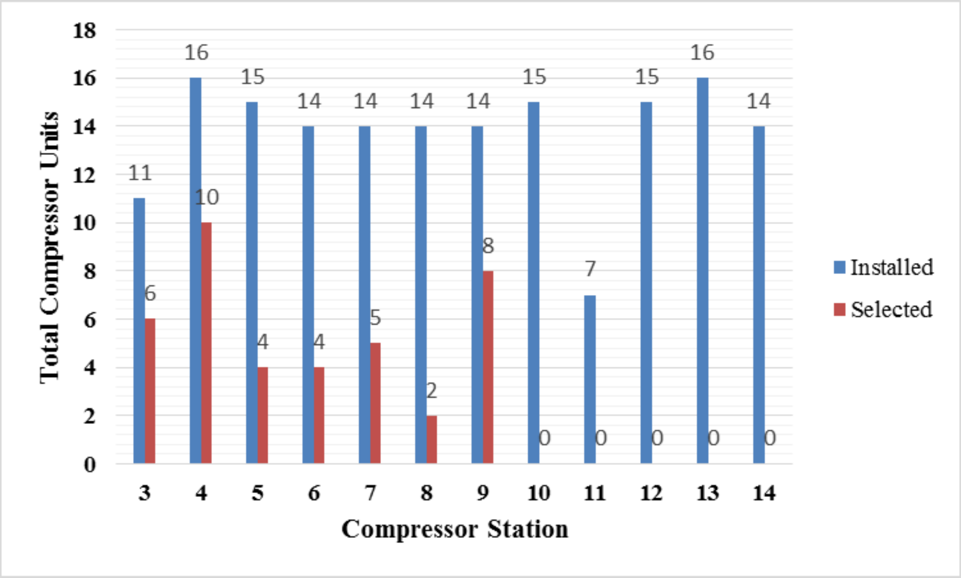


Figure 5.4: Compressors Installed Vs. Compressors Selected for Scenario 1

Through the optimization, it is found that only 25% (135500/548400) of the installed HP is required to satisfy the peak demand and only 24% (39/165) of the compressors are required. Thus, given the assumptions, the existing Gas Transmission Pipeline System can be operated much efficiently by selecting the right combination of suction pressure and compressor used. The network might have the additional capacity in order to handle situations like introduction of contract pressure which might require additional compressors and also to meet future demand, which is projected to be more than the current demand.

Results of Scenario 2:

As discussed in the literature review, in reality, the pipelines are not always laid straight, but there may be an elevation difference between two nodes of the pipeline. To understand the effect of elevation of pipeline on the objective function value, pipeline elevation has been built into the Scenario 2 model. The relative elevation between the nodes are assumed and are shown in Table 5.5. The model was solved using GA and OptQuest with RP_n , B_{njk} and D_p as decision variables while considering these elevation differences. The compressor units selected and pressure values are shown in Table 5.9 and 5.10, respectively.

Table 5.9: Results of Scenario 2: Compressor Units Selected

Station #	Node	Total HP Selected	No. of Compressors Selected				
			100 HP	1500 HP	2000 HP	4500 HP	7500 HP
3	Eastport	25000		1	2	1	2
4	Sandpoint	32000		3	4	1	2
5	Athol	24000		1			3
6	Rosalia	18000		1		2	1
7	Starbuck	20000		1	1	2	1
8	Wallula	5500		1	2		
9	Ione	12000		8	0		

Table 5.10: Results of Scenario 2: Inlet and Outlet Pressure at each Nodes

Station #	Node	Pipeline Inlet pressure	Pipeline Outlet/ Station Inlet Pressure	Station Outlet pressure
-	Kingsgate	1181	1181	1181
3	Eastport	1181	1171	1363
4	Sandpoint	1363	1189	1443
5	Athol	1443	1292	1496
-	Spokane	1496	1426	1426
6	Rosalia	1426	1322	1494
-	Palouse	1494	1412	1412
7	Starbuck	1412	1295	1491
8	Wallula	1491	1374	1428
-	Stanfield	1428	1369	1369
9	Ione	1369	1277	1410
10	Kent	1410	1308	1308
11	Madras	1308	1177	1177
12	Bend	1177	1054	1054
13	Chemult	1054	885	885
14	Bonanza	885	620	620
-	Klamath Falls	620	620	620
-	Tuscarora	620	574	574
-	Malin	574	565	565

The objective function value found using GA is \$488.5 Million which is \$3 Million more than that found in Scenario 1, which does not consider the effect of pipeline elevation. Also, the value of D_p was found to be 48”.

It was found that a total of additional 1000 HP at Stations 8 and 9 together is required to successfully transmit the Natural Gas in Scenario 2, when compared to Scenario 1. At Station 8, an additional 1500 HP compressor was selected and at Station 9, a 2000 HP compress was unselected and a 1500 HP compressor was selected. This can be observed from Table 5.6 and Table 5.9. The additional capacity was selected in order to ensure that the outlet pressure at Station 14 (620 psig after optimizing) does not fall below 600 psig (constraint). The additional compressor was selected at Station 8 and not in any other station because of the severity created by combination of elevation, distance from next Station and unavailability of small size (1500 HP) compressors at Station 8. That is, from Station 8 (Wallula), gas has to be transmitted to the outlet node Stanfield and then to Station 9 (Ione), which is at an elevation of 45 feet. Also, the total distance to transport the gas is 63.9 miles. The only other Station that has a comparable severity is Station 6 (Rosalia), which has to transmit gas to 69 miles and to an elevation of 75 feet. It makes sense to make an extra 1500 HP compressor to run at Station 6. But, Station 6 does not have any additional 1500 HP compressor available. If an additional 2000 HP compressor was selected, the fuel cost will increase. Hence, the additional compressor was selected to run at Station 8, which has the second highest severity.

This explains that it is important to consider the effect of pipeline elevation while solving the Natural Gas Pipeline Transmission network problem. The importance of considering the elevation difference grows exponentially with the increase in relative elevation between the nodes. If the relative elevation between nodes are high, the optimal selection of compressors might be significantly different compared to the scenario in which the elevation is not considered. A comparison of the total installed HP in the existing network vs. the selected HP through the optimization is shown in Table 5.11. Also, the comparison of compressors installed vs. the compressors selected is shown in Figure 5.5.

Table 5.11: HP Installed Vs. HP Selected for Scenario 2.

Station #	Installed HP	Selected HP
3	51500	25000
4	48600	32000
5	49300	24000
6	47800	18000
7	54000	20000
8	51600	5500
9	28200	12000
10	47900	
11	25100	
12	64700	
13	48100	
14	31600	
Total	**548400**	**135500**

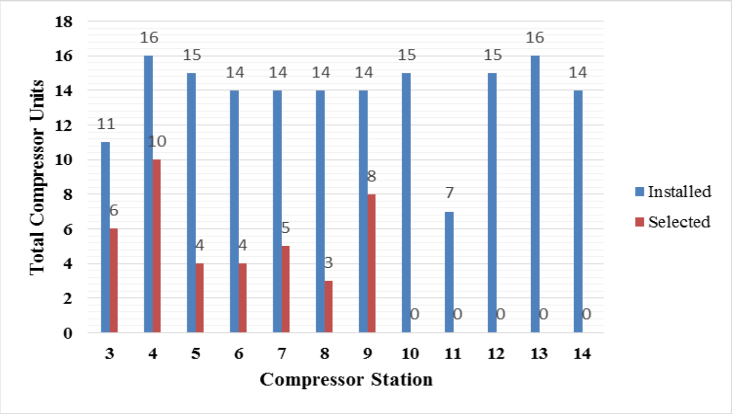


Figure 5.5 Compressors Installed Vs. Compressors Selected for Scenario 2

It can be seen from Table 5.11, that the Horsepower requirement is only 25% of the installed capacity.

5.2.4 Variability of Objective Function with Inlet Pressure (RP_n)

The main factors that affect the objective function value are the compressor selection and the suction pressure. Since the network has excess compressor capacity, the resource constraints are non-binding and hence Sensitivity analysis was not performed.

The impact of variability of the suction pressure on the objective function for Scenario 1, using GA is shown in Figure 5.6. If the suction pressure is maximum, the power required to transport the Natural Gas to the delivery nodes should be minimum. However, it has been found from Figure 5.6, that it is not the case. This might be because of the pipeline and compressor constraints involved. These constraints cannot be relaxed because of pipeline design guidelines and specifications. Hence, running an optimization model before maximizing the inlet suction pressure to confirm the feasibility is recommended.

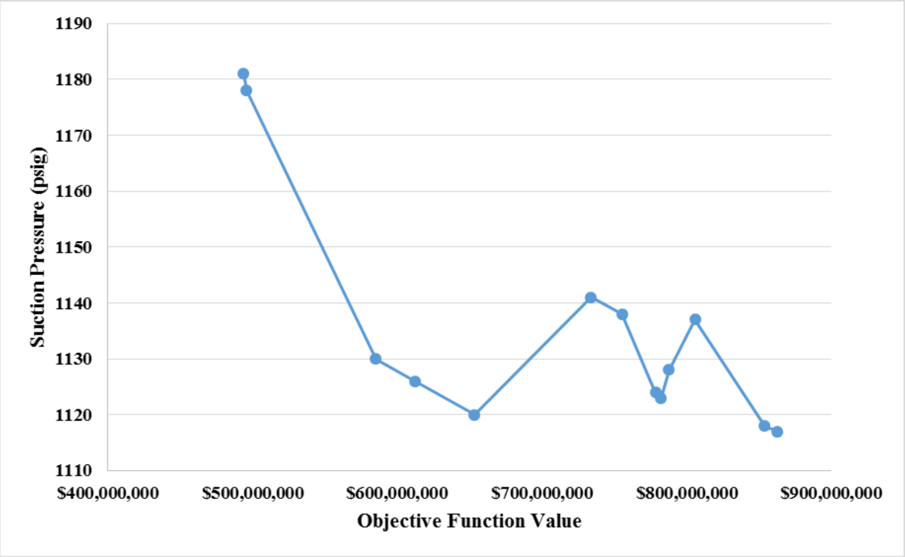


Figure 5.6: Variability Analysis: Inlet Pressure Vs Objective Function Value

5.3 Observation on Usage of Algorithms

This section discuss the observations gathered by running the model for Scenario 1 in Microsoft Excel, using the add-in Evolver version 6.4 and Solver. Also, the two scenarios of the model were executed in the Excel add-in Evolver, using OptQuest and GA independently, with the same initial parameter values.

The results of the scenario in which the pipeline network was working at maximum capacity obtained using GA and OptQuest are shown in Figure 5.7 and Figure 5.8, respectively. The results show that GA performs a thorough search compared to OptQuest.

Figure 5.7: Result of Scenario 1 through GA using Evolver

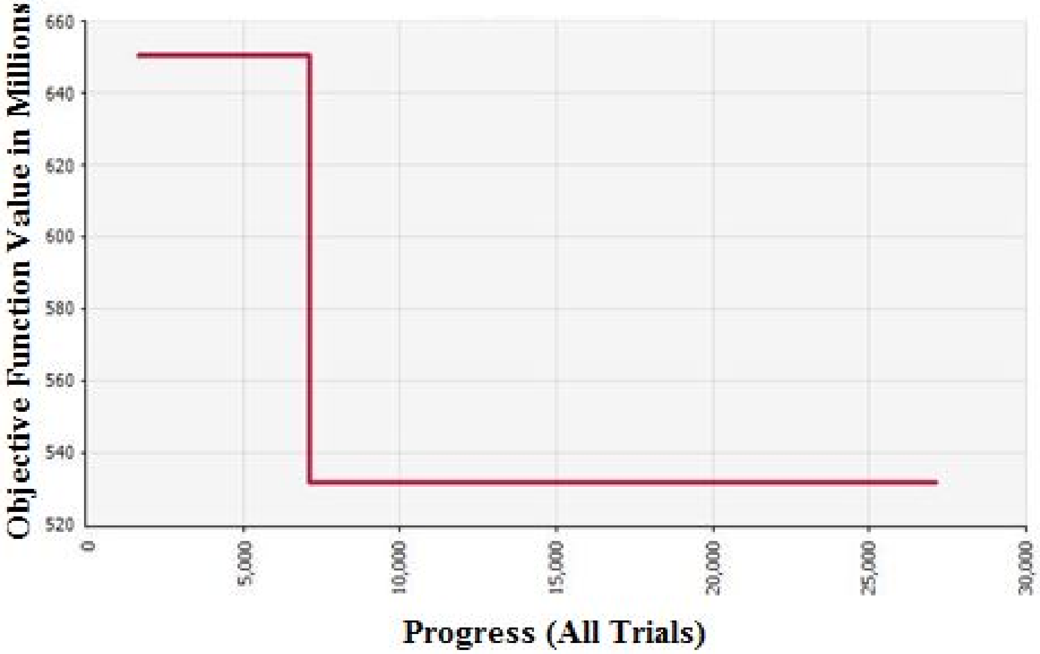


Figure 5.8: Result of Scenario 1 through OptQuest using Evolver

The optimal value obtained through GA and OptQuest was found to be $485 Million and $532 Million, respectively. For the same given set of initial values of parameters, GA was able to identify a solution that is 9.7% better than that generated by OptQuest. The summary of the 2 different scenario solved using GA and OptQuest is shown in Table 5.12.

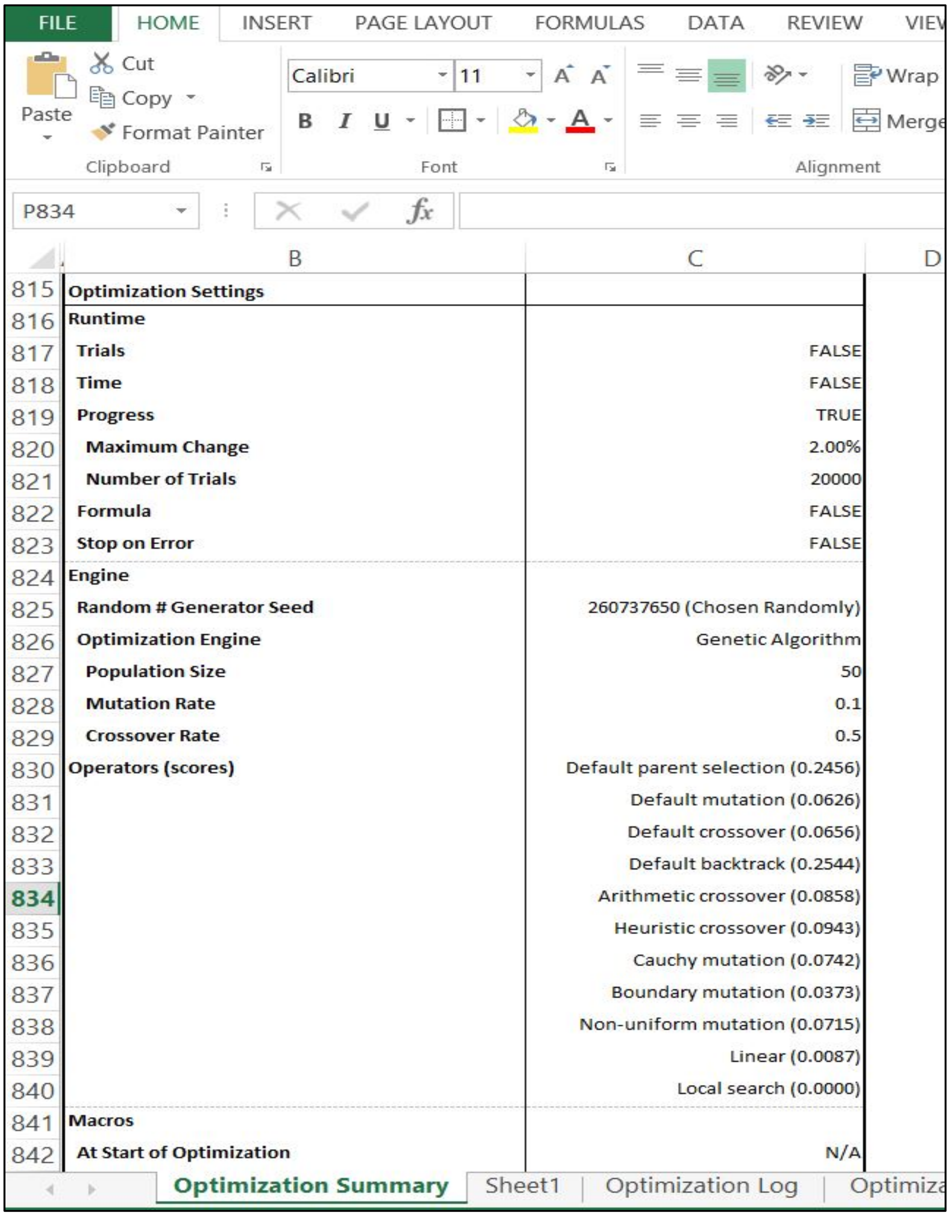
Table 5.12: Comparison of Performance of Genetic Algorithm and OptQuest

	Genetic Algorithm		**OptQuest**	
	Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
Objective function Value ($)	485 Million	488.5 Million	532 Million	587 Million
Time to find optimal	3333	3013	2257	1546
Trials to find optimal	23304	20088	7104	5965
Total Run time (Sec)	6565	3254	7386	6525
Total number of trials	37178	21804	27104	25965
Average Time/Trial (Sec)	0.18	0.15	0.27	0.25

The model was solved in a computer which had an Intel Core i7 3.2 GHz processor and 8 GB RAM. It is observed that GA gives better solution at a faster time and the average time to perform a trial is also significantly lower. It is to be noted that GA in Evolver does not support discrete values for the decision variables or the constraints.

Figure 5.9 shows a section of the summary output for Scenario 1, using GA. Evolver tested valid combinations of the above mentioned operators and identified the best performing operators. It is found that the top performing operators were the Default Parent Selection, Backtrack, Cauchy Mutation and Heuristic Crossover. This can be seen in Figure 5.9 by the values of scores for each of the operators. Also, the value of Trials/Generations and Times are ‘False’, because the optimization was manually terminated.

Even though Genetic Algorithm in Evolver does not support discrete variables, it still does a thorough search and gives better and faster results than OptQuest which uses Tabu search, Neural networks and scatter search. Hence, GA is preferred over OptQuest for the Natural Gas transmission system optimization model. This is also confirmed in Goldberg, (1987) and Sanaye and Mahmoudimehr, (2012).



	B	C
815	Optimization Settings	
816	Runtime	
817	Trials	FALSE
818	Time	FALSE
819	Progress	TRUE
820	Maximum Change	2.00%
821	Number of Trials	20000
822	Formula	FALSE
823	Stop on Error	FALSE
824	Engine	
825	Random # Generator Seed	260737650 (Chosen Randomly)
826	Optimization Engine	Genetic Algorithm
827	Population Size	50
828	Mutation Rate	0.1
829	Crossover Rate	0.5
830	Operators (scores)	Default parent selection (0.2456)
831		Default mutation (0.0626)
832		Default crossover (0.0656)
833		Default backtrack (0.2544)
834		Arithmetic crossover (0.0858)
835		Heuristic crossover (0.0943)
836		Cauchy mutation (0.0742)
837		Boundary mutation (0.0373)
838		Non-uniform mutation (0.0715)
839		Linear (0.0087)
840		Local search (0.0000)
841	Macros	
842	At Start of Optimization	N/A

Figure 5.9: Section of GA Summary Showing the Operators and their Impact

5.4 Scenario 3: Model with Full Set of Decision Variables

The Scenario 2 model was modified to have the full set of decision variables, which gives Scenario 3 which imitates the design of a complete Natural Gas transmission network. Considering the observations in Section 5.3, GA has been selected to solve this model. The Decision variables are as follows.

RP_n = Inlet pressure at receiving node ‘n’ (psig)

D_p = Inner Diameter of Pipeline (inch)

L_{an} = Length of pipeline ‘a’/distance between nodes ‘n’ and ‘n+1’ (miles)

B_{njk} = Binary variable for Compressor selection

B_{njk} = 1 if Compressor ‘j’ of type ‘k’ at node ‘n’ is selected

B_{njk} = 0 if Compressor ‘j’ of type ‘k’ at node ‘n’ is not selected

The objective function is minimization of the entire network cost. It is given by (20), which is $Z = \sum B_{njk} \text{ x } Y \text{ x } [MC_k + (FC_k \text{ x } 8760)] + [\sum L_{an} \text{ x } PC] + CC_k \ \forall$ (n,j,k).

The assumptions are shown in Table 5.4 and the default setting for the Generic Algorithm are the same as in Scenario 1 and Scenario 2, which is shown below.

- Population Size = 50
- Crossover Rate = 0.5
- Mutation Rate = 0.1

This scenario, when solved using the existing termination condition, gives an objective function value of $15.9 Billion over 20 years and $793.8 Million of compressor operations cost for a year. This value is 162% of the objective value of Scenario 2. Then, the model was executed by changing the termination condition to a maximum change of 0.1% over 20000 generations. With this termination condition, the objective function value was found as $9.67 Billion over 20 years and $482.3 Million of compressor operations cost for a year. This is 98.8% of the objective function value of Scenario 2. But the time taken to find the solution was 7 Hours and 30 Minutes compared to 50 Minutes for Scenario 2. The results of Scenario 3 is presented in Table 5.13. The comparison of values of results of Scenario 2, 3 and the existing network is shown in Table 5.14.

Table 5.13: Compressor Station Location and Compressor Selection

Station #	Station Location (Miles)	Total HP Selected	No of Compressors Selected				
			100 HP	1500 HP	2000 HP	4500 HP	7500 HP
1	55	23000	0	3	1	2	1
2	108	29500	5	3	4	2	1
3	172	29400	4	4	1	3	1
4	214	8100	1	4	1	0	0
5	277	20000	0	2	1	0	2
6	325	11200	2	6	1	0	0
7	482	9600	1	5	1	0	0
8	545	2300	3	2	1	0	0
9	599	3200	2	0	0	0	0

It was found that the value of the diameter of the pipeline was still 48”. It was also found that this particular network does not have a feasible solution for diameter less than 47” at the maximum flow condition. This iterates that to select the pipeline diameter, the design engineers of Gas Transmission Northwest LLC has followed a robust process. The value of the pipe thickness was calculated as 1”. The total number of compressors selected was 70 which accounts for 136300 HP. This is 25% of the total installed HP at the existing network. The MAOP value was found to be 1488 psig.

Table 5.14: Comparison of Values of Results

	Existing Network	**Scenario 2**	**Scenario 3**
Total # of Stations	12	12	9
Total Installed HP	548400	136500	136300
Minimized Fuel Cost ($ Million)	-	488.5	482.5
# of Compressors	165	39	70
Time taken to find optimal		3013	27000
Pipe Diameter (inch)	48	48	48

It was found that by considering the location of compressors as a decision variable, the total number of nodes required was reduced from 12 to 9. This means that the capital cost required to build the compressor station infrastructure can be reduced to 75%. Hence, it is important to optimize the entire system. These findings clarify that the model developed is working as desired in finding the optimal solution for all the decision variables and it has been understood that this model can be used for complex networks.

CHAPTER 6

CONCLUSIONS & FUTURE WORK

The objective of this thesis was to propose a modified compressor fuel cost minimization model that consists the MAOP and pipeline elevation. Also, a model for the entire pipeline network cost minimization was to be developed. Finally, the application of the proposed model was to be demonstrated on a real world Natural Gas transportation pipeline network.

The fuel cost minimization model in literature was improved to accommodate the effect of pipeline elevation and the safety constraint related to Maximum Allowable Operating Pressure. It was found that this model fails when the inlet pressure and the outlet pressure of the compressors are same. This is because the objective function is purely based on the pressure parameters while the compressor parameters are ignored. Hence, according to the model, even if the compressors are running, but do not do any adiabatic work, the fuel cost will be zero. The major assumptions made when developing this model include that the gas flows through each of the compressor stations. Because of these assumptions, every compressor station will be considered running even when it is not needed. To avoid this, a bypass condition has to be added when the gas pressure at the station is more than the required pressure to transmit the gas to the next station.

A new optimization model for the entire pipeline system that takes into consideration the pipeline diameter, inlet and outlet pressure at each nodes, compressor location, horsepower requirement, fuel cost and selection of compressors was proposed, to address the second research objective. This model eliminates the shortcoming of the fuel cost minimization model while not only minimizing the fuel cost but also the entire network costs. The assumptions in this model in addition to the steady state isothermal flow and constant compressibility and specific heat are that the compressors in a given station take in gas at a constant pressure, compresses and pushes the gas out at a constant pressure. Also, the diameter and thickness of the pipeline are assumed to be constant and the resale value of the assets are ignored. The diameter and thickness can be modelled to be variables across the pipeline network and this model can be extended to support the distribution network in addition to the transmission network.

The model proposed has been applied to the Gas Transmission Northwestern Corporations Gas transmission Pipeline Network and it has been solved in Evolver, using GA and OptQuest, which uses Tabu search, Neural networks and scatter search. OptQuest was used since it is the most commonly used optimization engine in simulation software (example: Arena and Simul8), the use of which is becoming a growing practice (Romo et al., 2009) and GA was used since it is one of the most widely used metaheuristic algorithm for solving complex optimization problems including Natural Gas transportation problems (Goldberg, 1987; Sanaye & Mahmoudimehr, 2012). Also, for the proposed model, it has been found that even though GA does not support discrete variable in Evolver, it still does a thorough search and works faster and provides better results than the OptQuest tool of Evolver and the best performing GA operators are found to be Backtrack, Cauchy Mutation and Heuristic Crossover. It has been found that the Natural Gas network analyzed can run at full capacity with just 25% of the existing compressors. This means that the remaining 75% of the compressors can be used elsewhere. It might be designed this way in order to satisfy the increase in the demand. This confirms that the model is capable of solving the problem that it was developed for.

Thus, the final research objective was achieved. From literature and the case study, it is clear that GA can be used for a much complex problems. It is to be noted that in order to apply this model in real world, in addition to answering to the assumptions, other technical aspects should be built into this model as constraints. These include the fuel consumption of the compressors at various loads and speeds, composition of the Natural Gas, flow reversal, etc.

Also, it has been found that the horsepower requirement to transmit the gas to the delivery node varied with the elevation. Hence, it is important to consider the elevation. In real world, the relative elevation between nodes might be very high and the optimal selection of compressors might be significantly different when compared with the scenario in which the elevation is not considered. The importance of considering the elevation difference grows exponentially with the increase in relative elevation between the nodes. It was also found that running an optimization model before maximizing the inlet suction pressure to minimize fuel cost is necessary to confirm the feasibility of transmitting the gas at an increased suction pressure.

It was also found that the impact of considering the location of the compressor stations as decision variables on the objective function is negligible (1.2% improvement) in the case study that was considered and for a given termination condition, the model gives a better result if the location of the compressor stations are not considered as decision variables. It is also found that if the location of compressor stations are considered as decision variable, the model takes approximately 8 times the processing time to give the results which is comparable with the model where the location of the compressor stations are fixed. Also, it might not be feasible to find the relative difference between all the possible nodes to use them as data for the proposed model. Hence, the decision of considering the compressor station locations as a predetermined parameter rather than a decision variable is based on the scale of the pipeline project. If the location of the compressor station are decided to be considered as parameters, the locations can be decided based on various factors including the general design guideline for distance between compressor stations, real estate cost, and proximity to inlet/outlet nodes. It is to be noted that selection of termination condition is crucial to find a good near optimal solution.

The model proposed can be extended to the distribution pipeline. But, it is expected to take significant time to solve the model to find optimal conditions. Hence, work has to done on the proposed model to produce optimal results in a short time. Also, research can be done to build the proposed model in simulation software, in order to accommodate the dynamic supply, demand and pressure conditions.

Also, since Oil and Natural Gas are explored and transported in similar way, opportunities to transport Natural Gas through Oil pipelines can be explored and the Network Cost Minimization model for this case can be researched. In addition to these, there are opportunities to optimize the system cost for off shore gas/oil transportation network by considering the scale of operations with the modes of transportation available, including pipelines, tankers, etc.

The proposed model considers only the economic part of the Natural Gas transportation system and does not consider the societal and environmental aspects. With the continuous growth in focus on sustainability, societal and environmental impact must be modeled into the proposed model by considering factors including potential impact on humans based on the area’s population density, environmental contamination, property damage due to explosions, etc.

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