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Optimal Network Design for Natural Gas Pipelines

by

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ABSTRACT

Natural gas transportation requires a continuous pipeline network from well-head to burner-tip. This work applies analytical network analysis techniques to the pipeline network design problem. Four issues receive attention: (1) central facility density, (2) spatially-optimal network design, (3) central facility placement, and (4) impact of environment on pipeline design. The first of these problems is solved using a market area model. Here, an appropriate configuration factor for pipeline networks is determined and used to calculated optimal density. Second, concepts of the minimal spanning tree and Steiner trees are combined in an analytical algorithm for generating near-optimal pipeline networks. Third, a standard optimisation process locates the network median for optimal facility placement. Last, monetary valuation of the environment is shown to have relevance to pipeline projects, and a revealed preference technique is proposed. Case studies of several Alberta pipeline networks illustrate the network concepts presented.

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DEDICATION

To Kirby.

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GLOSSARY OF TERMS

Absolute Centre	- That location in a network, either at a node or on a link, from which the maximum distance to all other network nodes is a minimum.
Absolute Median	- The location in a network, either at a node or on a link, from which the sum of distances to all other vertices in the network is a minimum
BCF	- Billion cubic feet.
Centre	- A node in a network from which the maximum distance to all other network nodes is a minimum.
Chain	- A set of connected links in a network which connect two points and do not contain a cycle.
Chromosome	- A coded descriptor which uniquely describes a potential problem solution, used in genetic algorithms.
Colatitude	- The complement of the latitude.
Complete network	- A connection of points in which there is a path between every pair of points.
Configuration factor	- A mathematical factor used to represent the travel distance metric in effect, and the shape of the market area being investigated using the General Optimal Market Area model.
Crossover	- The "mating" of two chromosomes in the genetic algorithm which splits two chromosomes and exchanges one part of each with the other to create two "offspring."
CVM	- Contingent Valuation Method.
Cycle	- A set of links in a network which start and end at the same node.
Deep-cut plant	- A gas processing facility which removes heavier hydrocarbons (C2+) from the natural gas stream beyond the requirements for pipeline transportation.
Directed network	- A network composed of one-way links.
Distance table	- A table which displays inter-nodal distance at the cross-over of the column and row representing each of the two nodes.
ESA	- Environmentally sensitive area.
EUB	- Alberta Energy and Utilities Board
FST	- Full Steiner tree.

Full Steiner Tree	- A Steiner tree which has the maximum number of Steiner points (n + 2).
Gathering System	- A pipeline network which collects raw gas from individual wells and transports it to a gas plant at which the gas is processed to meet pipeline quality standards.
GDP	- Gross Domestic Product.
Genetic algorithm	- An heuristic algorithm which approximates Darwin's theory of evolution (survival of the fittest) to determine the best problem solution.
GOMA	- General Optimal Market Area model.
Graph	- A network.
GRI	- Gas Research Institute.
HPF	- Household production function.
HPM	- Hedonic price method.
Hub	- A central facility at which inbound and outbound links meet.
Inbound link	- A pipeline link which carries gas into the central facility.
Interconnect	- The point of connection between two pipelines, usually pipelines of large scale.
km	- kilometres
LDC	- Local Distribution Company.
LNG	- Liquefied Natural Gas.
LPG	- Liquefied Petroleum Gas.
Lateral	- The pipeline which connects a gas plant to the trunk pipeline.
Latitude	- The angular distance north or south of the equator.
Longitude	- The angular distance east or west of a standard meridian.
MCF	- Thousand cubic feet.
MMCF	- Million cubic feet.
MST	- Minimum Spanning Tree.
Market Center	- A facility at which large quantities of gas, many buyers and many sellers exist for the purpose of buying, selling and shipping gas.
Median	- A node in a network from which the sum of distances to all other vertices in the network is a minimum.

Minimal spanning tree	- A spanning tree which connects a set of vertices using the shortest total link length and which uses no Steiner points.
Mutation	- A process used in genetic algorithms which changes "offspring" by one "gene" with a very low probability, just as genetic mutations occur in the natural world.
Network	- A system of nodes and inter-connecting links.
NGTL	- NOVA Gas Transmission Ltd.
NOVA	- The company which owns and operates the only trunk pipeline in Alberta.
NPV	- Net present value.
O/D	- Origin/Destination.
Outbound link	- A pipeline link which carries natural gas products out of the central facility.
Path	- A connected set of links between two nodes in a network.
Pruning	- A computational technique which reduces the solution space prior to full solution determination, thereby reducing the total number of calculations needed.
RAM	- Random Access Memory
Route	- A set of connected links in a network which connect two points and do not include a cycle.
RP	- Revealed preference.
Sales Gas	- Natural gas which is suitable for both long-distance pipeline transportation and consumption by customers.
SMT	- Steiner Minimum Tree.
Sour Gas	- Natural gas containing hydrogen sulphide.
SP	- Stated preference.
Spanning tree	- A tree network which spans, or connects, every node in the space.
Steiner minimum tree	- A Steiner tree which is made up of the shortest possible total link length, accounting for all topologies.
Steiner point	- A point used in a Steiner tree which is not part of the original problem set and which forms part of the connecting tree to shorten the total network length.
Steiner tree	- A tree which contains the known set of vertices and another set of points, called Steiner points, to reduce the total link length of the connected network.

Sweet Gas	- Natural gas which is free of hydrogen sulfide.
TCPL	- TransCanada Pipeline Ltd.
Topology	- The set of connections between vertices and Steiner points; the locations of the Steiner points are not specified.
Tree	- A complete network which contains no cycles.
Trunk pipeline	- A large pipeline system which collects sales gas from gas plants and transports it to a long-distance pipeline.
Undirected network	- A network which contains only two-way links.
WTA	- Willingness to accept.
WTP	- Willingness to pay.

CHAPTER 1

INTRODUCTION

It is essential as a matter of simple survival that we understand science ...
evolution has arranged that we take pleasure in understanding
- those who understand are more likely to survive.

from Carl Sagan's *Cosmos*,
1980, New York: Ballantine Books, p. xvii.

Pipelines, and their networks, are not typically designed by transportation engineers. Perhaps it is not surprising, then, that the subject of pipelines has not received great attention from transportation researchers.

Optimization of pipeline operations has traditionally been approached from inside the pipe. Understanding flow in pipes, friction reduction, proper placement of pumps and compression, and proper material selection are common examples of this focus. This work casts a different light on the pipeline optimization problem by looking at it from the perspective of a transportation engineer: How can the design of the pipeline network layout contribute to overall system efficiency?

Pipelines are most heavily utilized for transportation of petroleum and petroleum products. Of all petroleum products, natural gas relies most heavily on pipelines because of its gaseous nature. Here, the research focus is placed on natural gas pipelines; however, most of the concepts may be applied, with little modification, to other pipeline systems.

1.1 Problem Definition

The purpose of this research is to expand current pipeline industry practice by developing a straightforward method of locating central pipeline facilities and designing pipeline networks. Central facility location and pipeline network design are difficult to separate since the facilities are integral network components. For this reason, both problems receive equal attention.

1.2 Scope

A network is a system of nodes and inter-connecting links. This thesis studies the relationship between these nodes and links in a gas pipeline network. Specific attention is given to pipeline link layout design, density and location of central facilities in the network, and the impact of environment on network layout design. Pipeline networks of different scales are discussed and studied.

The following problems are discussed in detail:

(1) identification and comprehension of the components of pipeline networks as they apply to the network problem,
(2) determination of appropriate facility density in a pipeline network,
(3) development of a method for identifying near-optimal pipeline routes,
(4) development of a method for optimally locating central facilities in a pipeline network,
(5) development of a method for incorporating environmental considerations in pipeline network design, and
(6) illustration of the above methods using local case studies.

A similar problem and procedure were used by Wirasinghe and Vandebona (1988) in planning underground subway transit systems. In this example the optimal number of stations, their locations, and then the optimal subway network to connect them were determined using similar analytical procedures as are explored herein.

1.3 Content Organization

The content of this thesis is arranged as follows. Chapter 2 establishes the background to the pipeline network optimization problem, and introduces important terminology. Chapter 3 presents related research ideas which have achieved publication, and shows their importance for the current research. Chapter 4 focuses on the problem of calculating the optimal density of gas processing plants in a gas pipeline network. Chapter 5 explores the question of optimal pipeline network design, including a case study of the Amoco East Crossfield gas gathering system. The problem of optimally locating central facilities within a pipeline network is examined in Chapter 6, where the study of the East Crossfield system continues. Techniques for incorporating environmental costs into the optimization procedure dominate Chapter 7, and a new revealed preference techniques is demonstrated using the Palliser Pipeline Project as an example. Finally, Chapter 8 contains the conclusions and recommendations emerging from this research.

CHAPTER 2

GAS PIPELINE BASICS AND TERMINOLOGY

> *A new element! It was a fascinating and alluring hypothesis - but still a hypothesis. For the moment this powerfully radioactive substance existed only in the imagination of Marie and Pierre. But it did exist there.*
>
> From Eve Curie's *Madame Curie*,
> translated by Vincent Sheean, 1946,
> New York: Pocket Books, pp. 165-66.

2.1 The Structure and Operation of Gas Pipeline Networks

Natural gas is produced from wells drilled into hydrocarbon-bearing geological structures beneath the surface of the earth. Natural gas is composed largely of methane, and usually contains a limited number of impurities such as oxygen, nitrogen, carbon dioxide and sometimes hydrogen sulfide which are natural byproducts of gas production.

Natural gas is transported from the well, where it is produced, to the burner-tip of the end user through a number of inter-connected pipeline networks. Because of it's gaseous nature, natural gas must be transported through one completely interconnected pipeline system to avoid leakage to the atmosphere. The system which transports this gas is comprised of a number of networks within each other. These networks are described below.

To begin, natural gas produced from wells is collected and shipped to a processing plant where moisture and impurities are removed from the gas before it is shipped farther downstream. The network connecting a number of gas wells to a processing plant is called a gathering system. In this arrangement the plant acts as a hub. A hub is a central facility within a network. The plant, or hub, receives incoming gas from gathering pipes, and feeds a smaller number of processed streams exiting the plant. Some of these processed streams might include processed gas, sulphur, and liquefied petroleum gases.

Processed gas from many plants is collected by a larger pipeline system, sometimes called a trunk line. A trunk line might have a number of destinations to which processed, or sales, gas is delivered. At this time in Alberta, NOVA Gas Transmission Ltd. (NGTL) is the main gas trunk line and collects most of the sales gas within the province. Within Alberta, NGTL delivers gas to local distribution companies, industrial end users, and other users of natural gas. As well, gas is exported from Alberta for consumption in the Canadian and US markets. Long-distance pipelines such as TransCanada Pipeline and Alberta Natural Gas Pipeline intercept the gas at export points and carry it to distant markets and farther downstream pipelines.

Long-distance pipelines, or inter-state pipelines as they are called in the United States, form a complete network which links every supply and demand region in North America. At some pipeline interconnects (the location at which two pipelines connect) market centres have emerged. Market centres are trading spots at which a large volume of gas, many buyers and many sellers all exist together.

The gas is propelled along a pipeline by virtue of differences in gas pressure. High pressure gas flows in the direction of lower pressures. In this way, gas compression (or liquid pumps, in the case of liquid pipelines) is used periodically to increase the gas pressure, essentially pushing the gas farther downstream.

Underground storage facilities fill an important role in the natural gas transportation system, also. Natural gas demand experiences large fluctuations due to weather and the relative prices of natural gas and oil, to name a few factors. In Canada, winter gas demand for heating is much higher than summer demand; in the southern parts of the United States summer gas demand is higher because of the increased need for air conditioning. Storage use keeps pipeline requirements lower and well-head production rates constant, while still meeting the volume demand fluctuations at the market.

Distribution of natural gas to most residential, commercial, and industrial consumers is done through distribution systems, usually owned by Local Distribution Companies (LDCs). Distribution systems are similar to gathering systems except they are usually much larger in scale, and homes and businesses are connected to the network instead of gas wells.

2.2 **Unique Aspects of Gas Pipeline Networks**

Pipeline transportation is unique in the transportation industry. The following five sub-sections describe some of the important differences which make pipeline networks worthy of individual study in the field of transportation networks.

2.2.1 Mode Captivity

Natural gas is captive to the pipeline mode of transportation because of its gaseous state. Liquefied natural gas (LNG) can be transported via truck or ship, but LNG is expensive to produce and must be shipped at a very low temperature making this option prohibitively expensive in most cases.

Mode captivity in the gas transportation industry impacts gas pricing directly. As with transportation of goods in general, improved efficiency in gas transportation methods will directly result in reduced costs and, therefore, pricing. However, because of the lack of competition from other modes for gas shipping this industry may not incorporate efficiency improvements as quickly as might occur in more competitive arenas.

2.2.2 Continuous Transportation System

Pipeline networks are continuous structures which can receive or deliver gas volumes at any point along the route so long as the necessary mechanical components exist at that location. These components include a valve and metering device with downstream pipeline connections. Continuous transportation systems contrast with discrete systems in which receipts and deliveries may only be made at certain drop-off and pick-up locations. An example of this is an airline route in which passengers and baggage may only board or exit an airplane while it is landed at an airport.

2.2.3 Natural Gas as a Commodity

Natural gas measurement in North America is moving away from quantification in terms of volume, and towards quantification in terms of energy. One molecule of methane is identical to any other methane molecule. However, most natural gas contains a percentage of impurities which do not contribute to it's energy value, such as carbon-dioxide. Also, natural gas may contain a quantity of heavier hydrocarbon molecules, such as ethane and propane, which enhance the energy content of the gas. By measuring natural gas in energy, it is possible to capture the whole heating value of the gas.

Natural gas owners who ship their gas on third-party pipelines never receive the exact gas molecules delivered to the pipeline at the upstream end. Their gas molecules commingle with other molecules along the way. By using energy measurement techniques, however, gas owners are assured to receive the same gas value at the downstream pipeline end.

Because one unit of energy may be traded for another unit of energy, gas is a commodity which may "travel" by virtue of being traded for an equal energy quantity at another location, without physically traveling the distance between those two locations.

2.2.4 Time of Transport

In the gas pipeline industry time of travel is of no consequence. Because gas receipts are blended along the length of the pipeline, pipeline operators allow shippers to benefit from "instantaneous delivery." In other words, as soon as a quantity of gas is received by a pipeline it instantaneously displaces the same volume of gas at the delivery point. Thus, the gas is considered to be physically delivered at the exact time it is received. Using energy measurement methods, gas owners receive the same heating value from the gas they receive back from the pipeline, even though it is not the exact gas they originally delivered to the pipeline.

The insignificance of gas transport time does not, however, imply that there is not some cost associated with transporting gas longer distances. It is true that consumers who live farther from the geological supply of natural gas pay higher prices for their gas than consumers close to gas production areas. This additional cost, however, is borne out of the costs of pipeline infrastructure and its operation, not from actual time of transport from well-head to burner-tip.

This system of inter-changeable natural gas molecules may be likened to the credit system used in banking. One does not withdraw the same dollar bill that was deposited previously. Another system, more analogous to pipelines, is the transportation of electricity. While electrons do not flow in the same manner as natural gas, it is clear that one electron is no different from another, and generation facilities may deliver different electrons onto the transmission network than are delivered to their specific customers.

In many other sectors of the transportation industry, however, time of travel is important and valued, such as for subway or airplane passengers, or for trucking of freight, especially perishable freight. There is an important distinction to be made between valued and non-valued travel time in transportation problems, and this should be clearly understood at the outset of the analysis.

2.2.5 Directed Networks vs. Undirected Networks

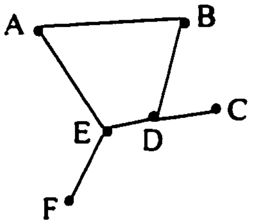
Pipeline networks are largely directed networks. A directed network is composed of links which flow in only one direction. An undirected network encompasses flow in both directions on its links. An urban road system which utilizes no one-way streets is an example of an undirected network.

Pipeline systems tend to be directed because they connect supply and demand centres, and flow is generally from supply to demand. There are, however, some bi-directional pipelines which enable flow in both directions. These pipelines can be useful when oversupply of one or more demand regions occurs, for example.

2.3 Terminology

This section outlines the basic terminology needed for the following discussion of networks. A network is a system of nodes, N, and links, L, between them. Networks are also sometimes called graphs. A network link between two nodes, i and j, is denoted (i,j).

An undirected graph is one in which all links are two-way; a directed graph contains some one-way links, and the direction of the link is always from i to j. The terms path, route and chain can all be used to refer to a series of links which do not pass through the same node more than once. A cycle is a path which starts and ends at the same node and does not pass through another node more than once. Figure 2.1 illustrates a link, path and cycle.



Link: A - E

Path: A - E - D - C

Cycle: A - E - D - B - A

Figure 2.1: A network showing a link, path and cycle.

A complete network contains a link between every pair of nodes, according to Newell (1973); however, much of the literature refers to complete networks as those having a path between every pair of nodes. Future reference to complete networks will imply the latter definition. A tree is a network which contains no cycles. Trees are common in pipeline and communications applications for networks. Fig. 2.2 illustrates the concept of a tree network.

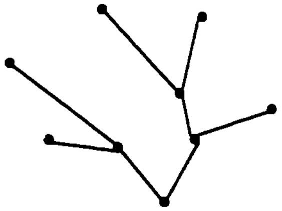


Figure 2.2: Tree network

Several types of tree networks are referenced in the literature. A spanning tree is a complete tree network, meaning a tree which has a path between every pair of nodes. A minimal spanning tree (MST) is a spanning tree for which the total link length is a minimum. Steiner trees are special trees which contain the nodes, N, as well as a number of other points, S, which are included in the tree in order to reduce the total link length beyond the minimum bound of the MST. The Steiner tree with the shortest overall link length is called a Steiner minimal tree (SMT).

Network terminology which is not included here is explained as required.

CHAPTER 3

REVIEW OF LITERATURE

> *There is a quilt pattern called Lady of the Lake, which I thought was named for the poem; but I could never find any lady in the pattern, nor any lake. But now I saw that the boat was named for the poem, and the quilt was named for the boat; because it was a pinwheel design, which must have stood for the paddle going around. And I thought that things did make sense, and have a design to them, if you only pondered them long enough.*
>
> Grace Marks in Margaret Atwood's *Alias Grace*, 1996,
> Toronto: McLelland & Stewart, p. 340.

3.1 **Introduction**

The review of literature summarizes a number of works in the field of networks which have application to pipelines. This chapter begins by reviewing publications related specifically to developments in the pipeline industry. The study of networks, however, encompasses more than just pipelines. Hence, the following sections contain a summary of published literature related to both transportation network optimization and optimal facility location. They include developments in each of the analytical, exact computational, and heuristic solution approaches.

3.2 **Gas Pipeline Research**

Accelerated growth in pipeline construction is expected due to recent industry deregulation in the United States. The growing presence of Mexico in the North American market is analyzed in George and Mortenson (1995). They anticipate private investment in Mexico's upstream sector followed by full integration with the continental natural gas market, in which Mexico is expected to be a net gas importer in the long term.

These developments indicate potential exists to improve the efficiency of gas pipeline systems in North America at all levels from gathering systems through to distribution.

Wearmouth (1994) found that, in 1993, 13 percent of Alberta's gas processing facilities, or gas plants, contained over two third's of the raw gas processing capacity in the province. Additionally, over fifty percent of Alberta's raw gas processing plants were designed to process less than ten percent of the total gas processing requirements. These findings alone indicate room for improvement in gas gathering network design and the location of raw gas processing facilities.

Bolkan (1991) developed a dynamic-programming model to optimize the design and operation of an oil pipeline. Only physical elements of the pipeline design were considered (pipe diameter, pumping stations, suction and discharge pressures). The pipeline route was not included in the optimization parameters. Bolkan found little published research on optimal pipeline design, and determined that the common industry practice for design involves a trial-and-error approach using cost-benefit analysis for comparison of alternatives. Her findings are consistent with those of the author in that little published research is available on pipeline optimization, and little of that relates to route design. There are few cases of published pipeline route optimization attempts, and those that exist utilize the trial-and-error approach.

The North American Regional Gas Supply-Demand Model was commissioned by the Gas Research Institute (GRI) in 1984, and is essentially a large-scale dynamic economic equilibrium model (Nesbitt, 1988). The model incorporates all supply and demand regions in North America in a network, the links of which represent pipeline corridors. These corridors include a number of separate pipelines connecting similar regions. This simplified representation, combined with the many difficulties associated with modeling the economy, make the model subject to large errors. Its main value is in sensitivity analysis and comparison of alternatives. The model is used extensively by governments and regulatory agencies for guidance in broad-range policy-making, but has limited value for regional applications. It is not a suitable model for determining the efficiency of the existing pipeline network. However, it might be useful to compare alternative scenarios for locating central facilities in the continental gas pipeline network.

The above publications touch on the fringes of the problem of interest in this work, that being the spatially optimal design of pipeline networks. However, pipeline industry publications appear to be lacking in the specific area of interest. The previous chapter made an analogy between the pipeline and electricity transportation systems. The latter of these systems was not the focus of the literature review, and, as such, may contain published research of some value to the pipeline problem being studied.

Notable differences between the electricity and natural gas transportation systems include (1) the generation of power is more concentrated than the production of natural gas, since single generation facilities would be designed to produce quantities of energy larger by several orders of magnitude than an average gas well, (2) loss of electrical power along the length of a transmission cable is an operational consideration in the field of electricity transmission which is not typically a concern in the transportation of natural gas (which may actually make minimisation of transport distance more significant for electricity), and (3) electricity demand fluctuates from one extreme to the other over the course of a day; demand for natural gas fluctuates more in response to weather and seasons than time of day.

3.3 Optimal Networks

Network optimization techniques have been studied extensively and applied in transportation, manufacturing, communication, and circuit-board design industries, to name a few. The problem is usually of this nature: How can a set of points be connected together with a system of links for the least cost? In the case of pipeline networks, the points are supply and demand locations, and the links are pipelines. The similarities and differences between this problem and others which utilize network optimization techniques are discussed. The overview highlights developments which have significance to pipelines.

3.3.1 Networks and Trees

The Steiner tree problem is one of the earliest and most difficult network problems. A Steiner tree is a network which connects a set of vertices (points), N, utilizing the shortest total link length by making use of some additional points, called Steiner points, S. The Steiner tree which has a globally minimal link length for the set of vertices, N, is called the Steiner minimal tree (SMT).

Bern and Graham (1989) give a brief history of the Steiner problem, attributing its origins to 17th-Century mathematicians Evangelista Torricelli and Francesco Cavalieri who, independently, solved the case of connecting three points to minimize total link length. They determined that if a single additional point, S, were placed amidst the three points and joined each of these at an angle of precisely 120° then the total link length would be minimized, as illustrated in Fig. 3.1.

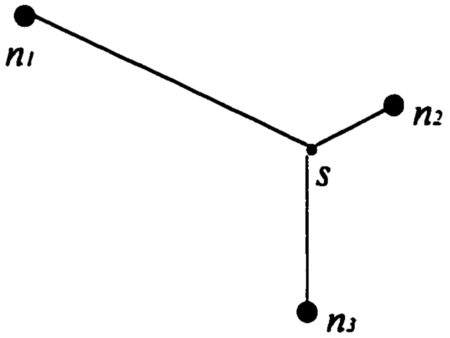
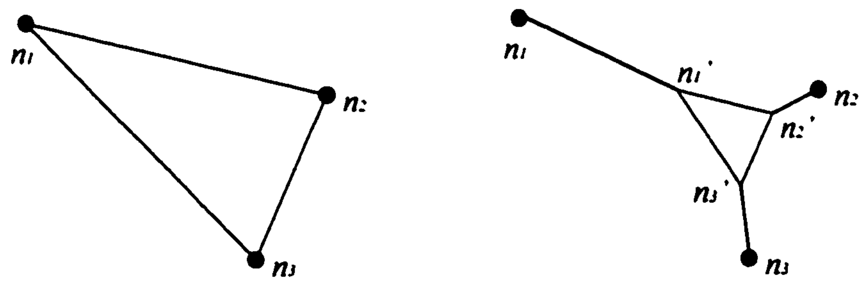


Figure 3.1: Steiner Minimal Tree for three points

The generalized problem was attributed to Jakob Steiner, a 19th-century mathematician at the University of Berlin, by Courant and Robbins (1941) in their book, *What is Mathematics?* Steiner sought out a single point which could minimize the total link length of a set of points.

Newell (1980) and Gatrell (1983) both show that the network shown in Fig. 3.1 is optimal if route construction costs dominate the decision-making process. However, if movement costs, i.e. vehicle operating costs, dominate then an optimal network between the same points would be as in Fig. 3.2a. Figure 3.2b shows an in-between case, but Newell states that the optimal situation always occurs at limiting cases, i.e. either Fig. 3.1 or Fig. 3.2a. In most transportation problems it is the fixed component of the system, the road, pipeline or rail line, for instance, which is more expensive than the mobile components. Certainly this is always the case for pipeline transportation, so it is Steiner's solution that is of greater interest here.



(a) high movement costs

(b) balance between movement and construction costs

Figure 3.2: Three-point networks for different movement costs

Weber (1929) used a Steiner construction to determine the optimal, and hence most likely, location of new industries. For a three-point problem he illustrated the location which would minimize transportation costs to and from a central site. He developed a method for weighting points to allow for different transportation costs.

Miehle (1958) uses two physical models to illustrate and explain link-length minimization for a network of fixed points. The first model uses fixed and mobile pegs attached by a string to find the optimal locations for a given number of Steiner points (the mobile pegs). The second model uses a soap film, which always forms to minimize its area, to determine optimal network design. The second method theoretically enables a global optimum to be found, since the number of Steiner points does not need to be predetermined. However, for large numbers of points Miehle found that the film geometry depended upon the inconsistent draining of solution from the apparatus. These simple physical models work well for small numbers of points, but break down for larger numbers - a problem researchers continue to struggle with.

Melzak (1961), a Canadian mathematician, proved that there exist a finite number of Euclidean constructions yielding all the minimal trees of the Steiner problem. A minimal tree is one which minimizes the total link length for a set number of Steiner points. These minimal trees are local minima; a locally minimal tree can be found for any number of Steiner points. The global minimum, the SMT, is the single local minimal tree which is the shortest of all. In his book (Melzak, 1973) he lays out a two-stage algorithm for determining the SMT. The first stage requires partitioning the set of points, N, into components (number of points ≥ 3) and residual points. The second stage solves the Steiner problem within each component and then joins the components and residuals together using shortest links. There is a finite number of combinations for stage 1, and a finite number of sub-combinations within each component for finding each Steiner tree. This algorithm is not efficient and cannot be used to solve a problem of many points.

Gilbert and Pollak (1968) proved several properties of SMTs. Among these were the lune property, wedge property, double-wedge property, minimal-spanning-tree line property, and diamond property.

A minimal spanning tree (MST) is a tree of shortest link-length which uses no Steiner points; a simple algorithm is known for finding the MST. Gilbert and Pollak (1968) conjectured that the lower bound for the length of the SMT could be represented by a ratio, ρ, of L_s/L_m where L_s is the length of the SMT and L_m is the length of the easily-computed MST. They put forward $\rho = 3^{1/2}/2 = 0.86603...$ and called it the ".86603... conjecture." Proof of this conjecture was finally given by Du and Hwang (1992). The result is significant because it proves that at most 13.4 percent improvement over the simple MST configuration is possible.

Cockayne (1970) proved that the SMT is made up of a set of components of full Steiner trees. Cockayne and Schiller (1972) present a working computer program using Melzak's algorithm. Using their program optimal networks for sets of up to seven points could be solved in five minutes or less using an IBM 360/50. Some eight-point problems could be solved in ten minutes. They give an example of a 21-point problem which was solved in ten minutes due to degeneracy into components of eight points or less.

Garey et al (1977) proved the computation of Euclidean SMTs to be at least as difficult as any *NP*-complete problem. *NP*-complete problems are varying and broad, but all have two important properties. Firstly, there is no known solution to an *NP*-complete problem which is solvable in polynomial time (on the number of points, n). Polynomial time refers to a calculation time which is described by an equation such as

$$a + b\mathrm{n}^{i} + c\mathrm{n}^{j} + \ldots \qquad (3.1)$$

where the superscripted power terms are constants. Problems which may be solved in polynomial time do not increase calculation time as rapidly as exponential time problems, as the number of variables increases. Exponential time problems are characterized by equations such as

$$a + b\mathrm{x}^{\mathrm{n}} + c\mathrm{y}^{\mathrm{n}} + \ldots \qquad (3.2)$$

As n increases, the calculation time required increases much more quickly with Eqn. (3.2) than with Eqn. (3.1).

Secondly, if any one *NP*-complete problem is proven solvable in polynomial time, then all *NP*-complete problems will be able to be solved in polynomial time. The rectilinear SMT problem, which uses only links aligned in the direction of two perpendicular axes, is also provable to be *NP*-complete using the techniques of Garey et al (1977).

The topology of a tree refers to the set of connections between the vertices, N, and Steiner points, S. The positions of the Steiner points are not specified in the topology, thus there is a relatively minimal Steiner configuration for each topology. The local Steiner minimal tree for a given number of Steiner points is one of the relative minima for that same number of Steiner points. The term topology, in this context, was introduced by Gilbert and Pollak (1968).

A highly successful pruning algorithm developed by Winter (1985) is used to evaluate and discard topologies which are sub-optimal before calculation of the relatively minimal Steiner tree is performed. Winter's routine has drastically reduced Steiner tree computation time. His program, GEOSTEINER, combines this pruning technique with Melzak's component selection to find SMTs for all randomly-generated 15-point sets in less than thirty seconds of calculation time. The technique is a two-stage algorithm. The first stage generates a pruned list of full Steiner trees (FSTs) which can possibly be in the SMT. The second stage determines the precise set of FSTs and their connections which make up the SMT.

Cockayne and Hewgill (1986) state that stage two of Winter's algorithm consumes the most calculation time and is thus the bottleneck to solving larger problems. They improve on stage two of Winter's GEOSTEINER algorithm so that stage one dominates the calculation time. Their improvements allow solution of all randomly-generated sets of up to seventeen points in less than 200 seconds using an IBM 4381 computer. They ran 100 randomly-generated sets of thirty points and found that twenty-one of them could not reduce to components of seventeen points or less. and thus would use unreasonable calculation periods.

Winter (1987) provides an extensive overview of exact and heuristic algorithms for solving the Steiner problem. It is evident from his review that little information is available for direct comparison of methods within and across the two classes. A large number of heuristic algorithms exist for computation of more realistically-sized point sets.

The most recently published work in the field of network design promote use of genetic algorithms to find optimal or near-optimal solutions. Genetic algorithms use Darwin's theory of evolution as a basis for their structure. Essentially, individuals seek out the fittest mate in order to procreate and give their likewise fit offspring a greater chance of survival.

Genetic algorithms solve problems by representing potential problem solutions as individuals. Each individual, or solution, has a unique genetic descriptor, or chromosome. In this case, a chromosome is a string of characters, or genes, each of which represents one element of the solution it represents. An optimal, or near-optimal, solution is found through successive "crossovers," or matings, of the chromosomes. Sometimes mutations occur which can reduce or improve the fitness of the offspring. Fitness of each solution is measured by a fitness function. Each generation of solutions is usually of the same size as the previous generation, with the less fit solutions being replaced by more fit. The most fit solution is always carried through until it is replaced or is found to be the best solution.

The genetic algorithm is superior to other heuristic algorithms because the crossing over and mutation of chromosomes enables offspring which can be very different from either parent. Since a locally optimal tree network is likely to have a drastically different structure from the global optimum, this aspect of the genetic algorithm is valuable.

Palmer and Kershenbaum (1995) present a tree-encoding style which they tested on sets of 6, 12, 24, 47 and 98 cities in the United States for determining the SMT. The results of their genetic algorithm far out-performed a random search technique, and matched or beat a chosen good heuristic technique for every problem.

The history of the Steiner tree problem presented here indicates that determining spatially optimal networks is a complicated and imperfect science. In addition, the pipeline industry does not prescribe to many of the solution principles, even simple ones, for design. In real route-design problems it is usually true that a finite number of routes are viable for consideration. Existing paths created by other industries (utility corridors, existing pipelines, roads ...) are preferred because there is less environmental damage associated with clearing the surface, access may be easier (especially along a road) and, thus, costs are reduced. For these reasons determining the absolute optimal route configuration for a pipeline network may not be necessary, especially since nearly optimal solutions may not look anything like the true optimum. Thus, the optimization techniques applied in this work subscribe to the general principles of the Steiner tree optimization problem, but do not search out global optimums using the techniques presented.

3.3.2 Facility Location - Medians

Gas pipeline networks contain processing and deep-cut plants, storage sites, and market centres. These facilities are integral components of pipeline networks to which all pipeline shippers need access. Optimizing their locations is part of optimizing the total network. For this reason, the literature available on the subjects of hub and central facility location are presented in this sub-section.

Hakimi (1964) defines the centre, absolute centre and median of a graph, and shows methods for determining these locations. He relates a graph center to the problem of locating a police station, where the object is to minimize the maximum distance to a point in the jurisdiction. The centre is that graph vertex which minimizes the distance to the farthest vertex. This type of problem is also referred to as a minimax problem. A center is located at one of the graph vertices; an absolute center may be located on a link in the graph, thereby achieving greater optimality.

A median is the point at which the sum of distances to all other vertices in the graph is a minimum. Hakimi uses the median to represent the location of a switching center in a communications network. He proves that for one median in a graph, the optimal location will always be at a vertex of the graph, not on a link. This result is significant for the current research because it is medians which are of greatest interest in the pipeline network problem, and Hakimi's result reduces the optimal solution space.

It should be mentioned that there is a fundamental difference between a communications network and a pipeline network: the former is an undirected network, the latter is directed. This may be explained by the fact that any node in a communications network may generate a signal and receive a signal, whereas there are generally no pipeline demand nodes which generate gas, and no producing nodes which receive gas (from another node, although well-head equipment may be fuelled with gas produced at that well). Hence, flow is from supply nodes to demand nodes, and not the other way.

In his later work, Hakimi (1965) presents a *p*-median problem in which a number, *p*, of "switching centers" are to be located in a graph so as to minimize total network length. He proves that only subsets of the points in the graph need be examined to determine an optimal *p*-median arrangement, thus extending his earlier (1964) result.

Goldman (1969) further extended these results for *p*-median locations to include the situation where a vertex could be a supply and/or a demand location. He also proved Hakimi's result holds for "postal" facilities which could require flow to pass through more than one central facility prior to its final delivery. Goldman and Witzgall (1970) show that a portion of a graph containing at least half of the "customer weight" must also contain at least one median in the *p*-median problem. Weight refers to values placed on the vertices of the graph which, in communication networks, might refer to the number of wires needed at that location. In a pipeline analogy it could refer to some measure of the supply or demand volume.

The rigour of Hakimi's result is further proven to include multi-commodity and multi-stage processing problems in Hakimi and Maheshwari (1972). These authors also state that the result is not inhibited by constraints on the network links, nor by route splitting; however, capacity constraints on the medians, themselves, will not uphold the result (unless more than one median may be located at the same spot).

Kariv and Hakimi (1979) prove that finding a *p*-median for a network is an NP-complete problem, but that it may be solved in polynomial time for a network which is a tree. They develop an algorithm which performs this function for a tree in $O(n^2p^2)$ time. Goldman (1971) gives an algorithm in $O(n)$ time for finding a 1-median of a tree.

At the same time as research was being conducted in locating *p*-medians, much work was also being done towards developing algorithms for solving the *p*-center problem, also known as the minimax facility location problem. First introduced by Hakimi (1964), further work has been done by Goldman (1972), Handler (1973), Dearing and Francis (1974), Hakimi et al (1978) and Jeger and Kariv (1985).

The median-location problem turns up in the pipeline industry when central facilities are being located in a pipeline network. Central facilities include gas plants, large-scale LNG (liquefied natural gas) extraction facilities, underground storage facilities, market centres or other large-scale facilities.

Medians, as opposed to centres, are studied because there is greater value in minimizing average travel distance to the central facility than there is in making the maximum travel distance smaller. Emergency services may require the latter for safety reasons, but there is little value in pipeline networks for such a quality.

The median-location concept is applicable in networks which have established links. It is the travel cost along these links which is used to determine the location of the median. Since pipelines are structures which have long service lives, and the networks are well-developed in North America, the median concept has many applications for the location of new central facilities. This is in contrast to the discussion in the next sub-section on hubs. The hub discussion focuses on techniques for locating central facilities amongst points when no links have been established.

3.3.3 Facility Location - Hubs

The concept of hubs has been extensively researched and applied in the airline industry. In fact, "hub" is a common term in the airline industry, and many passengers are familiar with hub stop-overs. The airline hub-and-spoke concept is based upon the convergence of many flights at a hub, switching passengers, and then departing for a number of non-hub destination cities, or second hubs. This method reduces the number of airplanes used, the total travel distance, and allows services, such as baggage handling, to be centralized for cost savings. It also, however, usually increases individual travel distance and time. Dott et al (1996) explore the similarities and differences between airline hubs and hubs used in the natural gas pipeline continental grid.

The location-allocation problem. as defined by Cooper (1961), is a set of destinations, the locations of which are known, which must be supplied by some sources. the number and location of which are unknown. Transportation costs are used to determine the optimum configuration of destinations and sources. Cooper. in his 1961 paper. uses Euclidean distance as the metric for shipping cost to develop an analytical solution to the problem as well as an iterative solution technique for large problems. As well, Cooper develops an heuristic solution approach using the fact that if the locations of all sources and destinations are known, then a solution becomes trivial. He suggests selecting a set of source locations. determining the optimal allocation. and repeating this for all possible source locations, or for all "important" source locations to find the optimal pattern.

Later. Cooper (1964) presents four heuristic solution techniques to his location-allocation problem, each of which is based upon a different technique for selecting the "important" source locations. The most notable of them is the "destination subset algorithm" in which only known destination locations are used as first approximations to the source locations. This approach is reminiscent of Hakimi's proof for optimal median locations. Testing of the four heuristic algorithms showed the destination subset algorithm provided the best results. Cooper's other works (1967. 1971) expand on the themes discussed here, and he develops two new heuristics which provide superior solutions but still use the destination subset method to obtain the first approximations to the solution.

Cooper's work is most applicable to distribution problems in which destinations, for instance a number of stores, are supplied by a smaller number of sources, in this example warehouses. In these problems the interaction of interest is only between the stores and the warehouses and not between warehouses or between stores.

Hodgson (1978) presents a location-allocation model for service facilities which strays from the typical assumption that patrons want to use the nearest facility. He reminds researchers that it is important to plan for realistic travel behaviour, not necessarily the most simplistic. It is most often we need to recall this warning when dealing with passenger transport, since passengers may make non-optimal travel decisions, or non-optimal from the viewpoint of the modeler. However, freight may also travel in a non-optimal fashion if we consider that humans are directing this transport, and may make decisions that are sub-optimal, or even irrational.

O'Kelly's work (1986a) expands Cooper's ideas to a network optimization scheme in which there exist hubs, defined as "focal points of a network through which inter-city flows become articulated." In a multiple-hub network there is interaction between hubs, unlike Cooper's problem in which there was no interaction between "warehouses."

O'Kelly (1986b) develops a solution for the problem of locating one and two hubs amongst origin/destination (O/D) locations. He chooses the locations of the O/Ds as initial estimates of hub locations and then splits the O/Ds into non-overlapping partitions using the perpendicular bisector of the line joining the two hubs, in the two-hub problem. He assigns all destinations to the hub in the same partition and then checks to see if there are any destinations which are closer to the hub in the other partition - the non-ideal case. All combinations of two-hub choices are investigated in this manner.

O'Kelly states, and it is obvious, that allocation of destinations to their closest hub may not be ideal when the purpose is not to reduce total distance traveled, but to achieve optimal network interaction. An illustrative example is the case where one O/D has heavy interaction with others far away and light interaction with those nearby. In order to optimize interaction in the network it might be advantageous to connect the O/D to a hub near those locations with which it is in frequent communication.

Aykin (1988) criticizes O'Kelly's nearest-hub allocation method on the basis that the nearest-hub allocation is a poor optimality assumption and illustrates mathematically the concept described in the preceding paragraph. For problems in which the level of interaction between O/Ds is inversely proportional to the distance between them, O'Kelly's method would apply.

O'Kelly's 1987 work broadens his earlier concepts to devise two heuristic solution techniques for the general multiple-hub location problem. The objective function is developed and a quadratic component represents the inter-hub connections. The heuristics developed use the O/Ds as hub locations and calculate total cost for all hub-location combinations with allocation to the nearest hub in one heuristic (Heuristic 1), and to the nearest and second-nearest hub in the second heuristic (Heuristic 2). Methods of reducing the computation time associated with calculating the quadratic term are presented. O'Kelly uses the technique to analyze airline passenger interaction data for 25 cities in 1970.

O'Kelly shows that a scaling factor, α, representing the economy of scale of the heavily traveled inter-hub links influences the hub location choice. Large economies of scale would be represented by α close to zero, and small economies of scale by α close to one. O'Kelly shows that heuristics 1 and 2 give similar results (i.e. nearest hub rule is good approximation) when $\alpha < 0.5$, that is when inter-hub flight costs are low on a per-passenger basis. When $\alpha \geq 0.5$ heuristic 2 gives better results. Aykin (1990) responds to O'Kelly (1987), criticizing his two-dimensional solution space for a problem which should realistically be represented in three dimensions due to its large scale.

Other research on the interacting hub location-allocation problem has been done by Aykin and Babu (1987) and Aykin and Brown (1992). The former work presents a solution technique for new facility location on a sphere, for application to problems covering large areas where the curvature of the earth becomes important. Both works test feasible new facility locations by area - an extension of the earlier works in which locations were restricted by a number of points. Consideration of facility location in three dimensions is a concept which would apply to pipeline networks since they traverse large distances on the earth's surface.

Also, Skorin-Kapov and Skorin-Kapov (1992) present an improvement to the heuristics developed by O'Kelley by using a tabu search method.

The main difference between the sets of literature presented on the cases of locating central facilities, call them medians or hubs, is the state of the network being evaluated. In the case of median location, the median was located in an existing network from which travel distances (costs) were measured. In the works presented on hub location, only node locations were specified since links would be established after the location of the hub was found. In the case of the airline industry, it is possible to realign links toward a new hub since air links are not fixed. In the case of pipelines, realignment of fixed links is prohibitively expensive. Thus, the hub concepts would be useful largely for new pipeline network design, and median-location concepts are applicable for existing networks.

As the North American pipeline grid is very mature, median location techniques for new facilities would be the most suitable method of design. Hub location techniques in the pipeline industry could find application in areas of the world which are just beginning to develop gas pipeline infrastructure. This research focuses on North American applications and case studies, so that median location has greater prominence in this work.

CHAPTER 4

PIPELINE FACILITY DENSITY

> *"IT'S LIKE ANYTHING ELSE ... IT TAKES GUTS. AND FAITH. ...*
> *FAITH WOULD HELP. BUT, IN YOUR CASE,*
> *YOU SHOULD CONCENTRATE ON THE GUTS."*
>
> Owen Meany in John Irving's
> *A Prayer for Owen Meany,*
> 1989, Toronto: Ballantine Books, p. 507.

4.1 Introduction

Facility location problems have two dimensions: (1) the number of facilities needed, and (2) the locations of the facilities. This chapter studies the first part of this problem using an analytical market area model which relies on some simplifying assumptions. This model aims to determine the optimal density of central facilities which serve all wells in its market area by considering transport cost from the wells to the facility as well as the cost to construct the facility. The second part of the facility location problem is studied in Chapter 6.

4.2 Market Area Model

Suppose we are confronted with the following problem:

> A large gas field has been developed by the drilling of many wells, and no gathering system is in place. The wells are distributed over the area with uniform density and production capability. Determine the number and

location of gas processing plants to minimize the total cost of "tying in" the wells and building the processing plant(s).

A gas field comprised of wells of identical productivity and uniform density over an area does not occur in practice, but this simplification enables the above optimization problem to be solved using elementary calculus. The objective is to minimize the construction cost of the plant and gathering system. Operating costs can be ignored if it is assumed that they are independent of the layout of the gathering system and the size of the processing plants.

Newell (1973) utilizes a suitable, analytical solution method for a number of engineering problems, including optimal number of transit stations, optimal number of warehouses and optimal number of distribution centres. Erlenkotter (1989) expands on this groundwork by developing a General Optimal Market Area model for a number of different market area shapes and distance metrics. His model uses simplifying assumptions, including the assumption that demand is uniformly distributed over an infinite plane, to calculate optimal facility density. It is this market area model concept which is applied to the subject pipeline facility optimization problem, much in the way Wirasinghe and Waters (1983) use this method to find the optimal number, capacities and locations of solid waste transfer stations for a city.

Analytical models, such as the market area model described above, utilize continuous functions, such as the uniform density profile, to generate problem functions which are solvable analytically. While these continuous functions often disallow the inclusion of real, discrete data, they are tools which can be used to further comprehension and quickly test trends which can be tedious and difficult to model using detailed, discrete computer-based models. This is not to say, however, that analytical models are better than discrete models, but rather that they are excellent complements. Geoffrion (1976, 1979) expresses this position when developing an analytical model for optimizing the number of distribution centres in a network, and applies the principles and model to several other industrial applications. Hall (1986) illustrates several different problem types which can benefit from the use of continuous or discrete approximations, and applies the continuous function to a model for optimization of transit station locations.

4.3 Calculating Optimal Plant Density

This section illustrates Newell's technique of determining optimal facility density, as used by Wirasinghe and Waters (1983) to determine optimal capacity and density of solid waste transfer stations. Erlenkotter's (1983) GOMA model performs the same functions as does Newell's, with illustration of the proper inclusion of different market area shapes, distance metrics and travel distance economies of scale.

Newell (1973) states that the average travel distance from a centroid to any point in the market area, A, served by the centroid is given by $kA^{1/2}$, where k is a factor for the shape of the area served. Newell provides k-factors for circular, hexagonal, square and triangular market area shapes, using the Euclidean distance metric. Erlenkotter (1989) explores this concept of shape factors in his development of a general market area model (GOMA). Erlenkotter labels Newell's k-factor the configuration factor, and shows the mathematical derivation of such factors for Euclidean and Manhattan distance metrics, for four different market area shapes.

Using Newell's average travel distance formula, the total cost per unit to transport gas from the wells to the plant, including the cost of the plant, may be explained by the following formula:

$$\frac{TC}{V} = \gamma k A^{1/2} + \frac{C(V)}{V} \qquad (4.1)$$

where: TC is the total cost to gather and process the gas,

γ is the transport cost per unit distance per unit volume of gas,

k is the market area configuration factor,

V is the volume capacity of the plant, and

$C(V)$ is the plant construction cost as a function of its capacity.

Equation 4.1 corresponds to Erlenkotter's derivation of average cost per unit of demand in the GOMA, with no economy of scale with travel distance. The analysis undertaken here excludes the operating cost of the pipeline and gas plant from the analysis because of the lack of data availability. If the data are available, it is straightforward to include the costs in the analysis simply by transforming the costs to a cost per unit time. Depreciation of capital costs is a useful technique for accomplishing this task.

The relationship between plant capacity and the wells in its collection area is:

$$V = \rho A \tag{4.2}$$

where: ρ is the density of gas production across the market area of interest.

Substituting Eqn. 4.2 in Eqn. 4.1 yields:

$$\frac{TC}{V} = \gamma k(V/\rho)^{1/2} + \frac{C(V)}{V} \tag{4.3}$$

The plant capacity which minimizes the total cost per unit of gas production may be found by differentiating Eqn. 4.3, setting it equal to zero, and solving the resultant equation. Before doing this, however, it is necessary to establish a relationship between the plant construction cost, C, and its capacity, V.

If we were to assume that no economy of scale exists for plant construction costs, a suitable representation of $C(V)$ would be a linear one:

$$C(V) = a + mV \tag{4.4}$$

where: a is the fixed cost of construction, and

m is the variable cost of construction.

Substituting for $C(V)$ from Eqn. 4.4 and differentiating Eqn. 4.3 yields:

$$\frac{d}{dV}(TC/V) = \frac{\gamma k}{2\sqrt{(\rho V_L^*)}} - \frac{a}{V_L^{*2}} = 0 \tag{4.5}$$

where: V_L^* is the optimal plant capacity for linear $C(V)$.

Solving for V_L^* yields:

$$V_L^* = (4\,a^2\rho / \gamma^2 k^2)^{1/3} \tag{4.6}$$

It is interesting to see that V_L^* is affected to a larger degree by the factors a, γ and k than by the well density, ρ, in Eqn. 4.6. It is unlikely, however, that the simple linear relationship describing the cost of plant construction is a realistic assumption.

There are two elements, then, which require careful consideration before applying the above optimization technique to the gas pipeline problem. These are:

(1) determination of an appropriate cost function, $C(V)$, to describe gas plant construction cost, and

(2) selection of the proper configuration factor.

The following sub-sections are devoted to each of these problems.

4.3.1 Gas Plant Cost Function

Published historical gas plant construction costs for the province of Alberta (Delta Hudson, 1997) were used to determine a reasonable representation of $C(V)$. Only plants with a raw gas capacity of 700,000 m^3/d (24.7 mmcf/d) or greater were included in the analysis, as these represent areas which serve a large number of wells. Different cost structures for gas plants which process sour gas (containing hydrogen sulfide) and sweet gas (containing no hydrogen sulfide) are reflected, since sour gas facilities are more process-intensive and, therefore, more expensive to construct.

By using historical gas plant construction cost data, and levelling it using the Gross Domestic Product deflator, we capture a picture of the cost of constructing gas plants in the past; but we do not necessarily have the best relationship for predicting or planning future development in Alberta, since construction costs have changed over time. Certainly, with improved processing technology, costs would tend to decrease over time; however, government and industry regulations have become more stringent over time (with respect to allowable emissions, for instance) making processes more expensive. For the purposes of this analysis then, the historical data may be considered a reasonable estimate of today's costs, since opposing forces have been at work to affect construction costs over time.

An alternative approach to establishing the $C(V)$ relationship might have been to establish a cost curve by directly approaching a gas processing plant manufacturer. This might be a suitable approach for refinement of the techniques presented, or for application to a specific development plan.

4.3.1.1 Sour Gas Plant Cost Function

Forty-three data points were used to estimate $C(V)_{sour}$. Equation 4.7 describes the relationship between sour gas plant capacity and construction cost revealed using a least-squares regression technique. The R-squared value for $C(V)_{sour}$ is 0.37, implying that 37% of the variation in the data may be explained by the following expression:

$$C(V)_{sour} = \quad 1.55 \times 10^{8}\,\mathrm{Ln}(V) - 2.17 \times 10^{9}, \qquad V \geq 12{,}000{,}000\ \mathrm{m}^3/\mathrm{d} \tag{4.7}$$

where V is measured in m^3/d. Equation 4.7 is valid for this analysis where $C(V)$ is greater than zero, or where V is greater than 1.2×10^{7} m^3/d (42 mmcf/d).

The calculated t-statistic for the parameter 1.55×10^8 is 4.910, and for the parameter -2.17×10^9 is -4.537. These statistics indicate that each of the parameters a and b are statistically significant at the 95% confidence level.

The relationship in Eqn. 4.7 accounts for a relatively small percentage of the total variation of the data. This low correlation is likely due to the difficulty of obtaining accurate construction cost data. Also, location, terrain and process-type are only a few of the many other factors which would have a large effect on plant cost, and they are not evaluated here. Figure 4.1 illustrates the data points used to derive Equation 4.7.

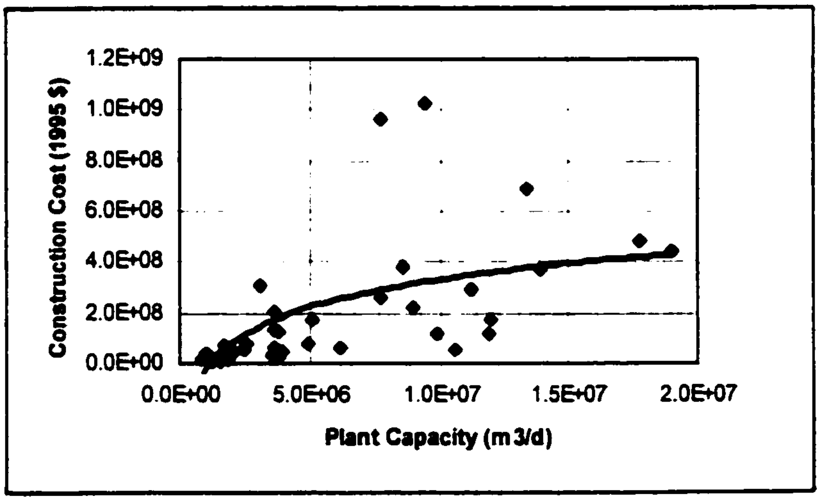


Figure 4.1: Sour gas plant capacity versus construction cost

4.3.1.2 Sweet Gas Plant Cost Function

Ninety data points were used to estimate $C(V)_{sweet}$. Sweet gas plants are more prevalent in Alberta, resulting in greater data availability than for sour plants. Equation 4.8 describes the relationship between sweet gas plant capacity and construction cost revealed using a least-squares regression technique. The R-squared value for $C(V)_{sweet}$ is 0.51, indicating that 51% of the variation in the data is attributable to the logarithmic relationship

$$C(V)_{sweet} = 2.39 \times 10^7 \,\mathrm{Ln}(V) - 3.19 \times 10^8, \qquad V \geq 6{,}300{,}000 \text{ m}^3\text{/d} \qquad (4.8)$$

where V is measured in m^3/d. Equation 4:8 is valid for this analysis where $C(V)$ is greater than zero, or V is greater than 6.3×10^6 m^3/d (22 mmcf/d).

The t-statistic for the parameter 2.39×10^7 is 9.663, and for the parameter -3.19×10^8 the t-statistic is -9.059, revealing statistical significance of the logarithmic relationship at the 95% confidence level. Once again, almost half of the data variability is controlled by factors not studied here. Figure 4.2 illustrates the data points used to derive Equation 4.8.

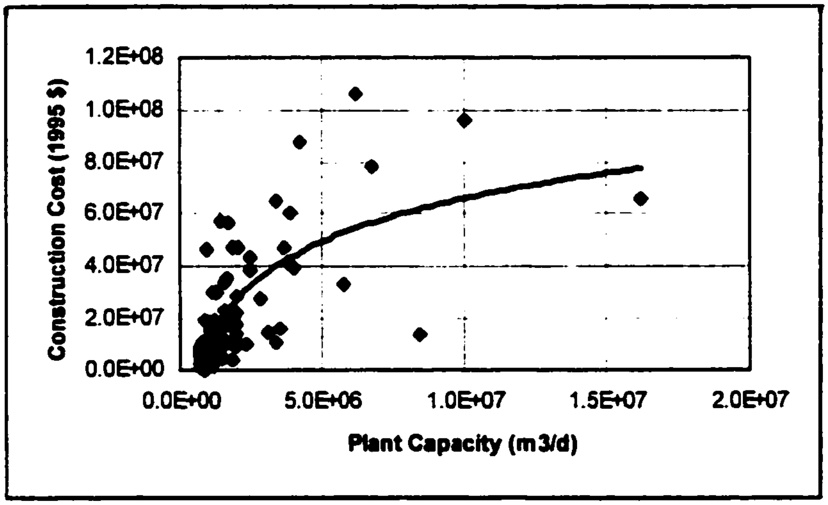


Figure 4.2: Sweet gas plant capacity versus construction cost

It is important to note that the distinction made herein between sweet and sour gas plants is a broad categorisation of a multitude of different processes which are used to purify sweet and sour gases. In other words, the two categories defined here are further divisible into many sub-categories corresponding to the actual processes used, each of which would have associated with it a different cost curve.

4.3.1.3 Optimal V using C(V)

The preceding two sub-sections determined the form of $C(V)_{sour}$ and $C(V)_{sweet}$ to be

$$C(V) = a \operatorname{Ln}(V) + b \tag{4.9}$$

with

$a_{sour} = 1.55 \times 10^8$,
$b_{sour} = -2.17 \times 10^9$,
$a_{sweet} = 2.39 \times 10^7$, and
$b_{sweet} = -3.19 \times 10^8$.

Substitution in Eqn. 4.3 yields:

$$\frac{TC}{V} = \gamma k (V/\rho)^{1/2} + \frac{a \operatorname{Ln}(V) + b}{V}. \tag{4.10}$$

Differentiation of Eqn 4.10 results in

$$\frac{d}{dV}(TC / V) = \frac{\gamma k}{2\sqrt{(\rho V^*)}} + \frac{1}{V^{*2}}[a - b - a \operatorname{Ln}(V^*)], \tag{4.11}$$

where V^* is the optimal plant capacity for C(V) of the form shown in Eqn. 4.9.

Setting the derivative of TC/V to zero results in the following equation:

$$\frac{\gamma k\, V^{*3/2}}{2\sqrt{\rho}} = b - a + a \operatorname{Ln}(V^*). \tag{4.12}$$

Having determined suitable values for a and b in the previous sub-sections, quantification of the remaining parameters will allow calculation of the optimal plant size, V^*. The parameter ρ may be calculated from field data on a case-by-case basis. Also, γ may be estimated to a reasonable degree from knowledge about the construction cost of pipelines connecting the wells to the plant. A suitable estimate of k, the configuration factor for the network, however, has yet to be found. The following section addresses this parameter.

4.3.2 Configuration Factor for Pipeline Networks

The configuration factors derived and used by Newell (1973) and Erlenkotter (1989) are based upon two common distance metrics: the Euclidean and Manhattan metrics, and upon five simple market area shapes: the circle, hexagon, square, diamond and triangle. The most efficient, packing market area shape for the Euclidean distance metric is the hexagon, and for the Manhattan metric is the diamond (Erlenkotter, 1989). However, it was also noted by Erlenkotter that the proper choice of metric is more significant than the choice of market shape.

Table 4.1 summarises Erlenkotter's (1989) configuration factors for four market shapes and two distance metrics, assuming no economy of scale with travel distance. The market shapes and metrics are abbreviated as follows: circular (C), hexagonal (H), diamond (D), square (S), Euclidean (E) and Manhattan (M).

Table 4.1: Configuration factors

Market Shape	**Distance Metric**	**Configuration Factor**
C	E	0.376
	M	0.479
H	E	0.377
	M	0.480
D	E	0.383
	M	0.471
S	M	0.500

Clearly, from Table 4.1, there is less variation of configuration factors across a given metric, than between metrics. The shorter, Euclidean, or straight-line, distance metric yields a lower configuration factor than the longer, Manhattan, or right-angled street, metric, implying that smaller configuration factors correspond to shorter average travel distance.

Figure 4.3 illustrates the market area concept using the hexagonal market shape. The closed dots represent the centrally-located gas plants, and the open circles are the gas wells, which would be uniformly distributed over the whole area. Within a given hexagonal area all wells would be tied into the plant for that area.

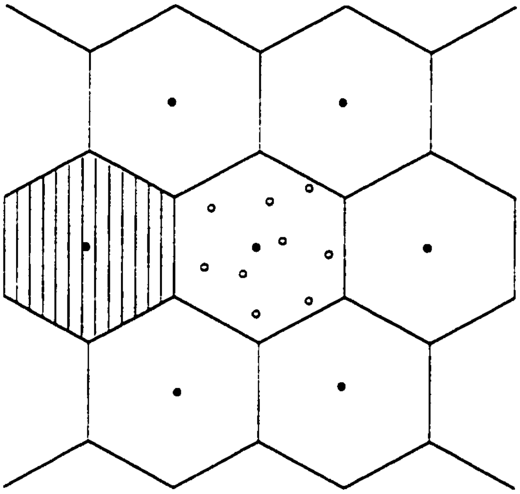
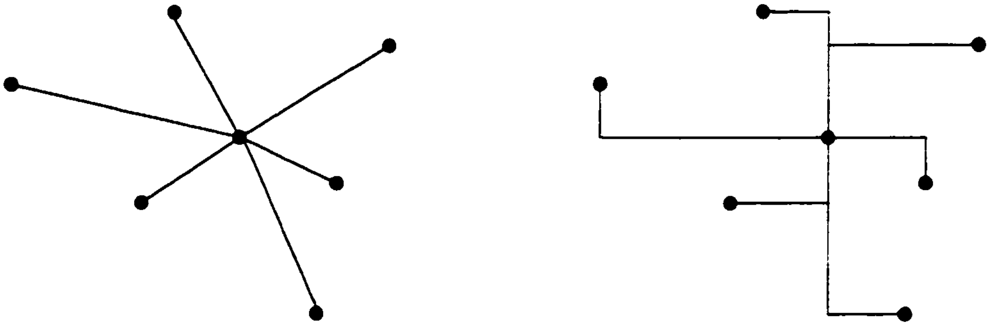


Figure 4.3: Hexagonal collection areas with plants as centroids

Visual inspection of the Euclidean and Manhattan distance diagrams shown in Figs. 4.4(a) and (b), and comparison to a typical pipeline network connection schematic shown in Fig. 4.5, reveals that neither are a good representation of the pipeline network problem.



(a) Euclidean distance metric

(b) Manhattan distance metric

Figure 4.4: Euclidean vs. Manhattan distance metrics

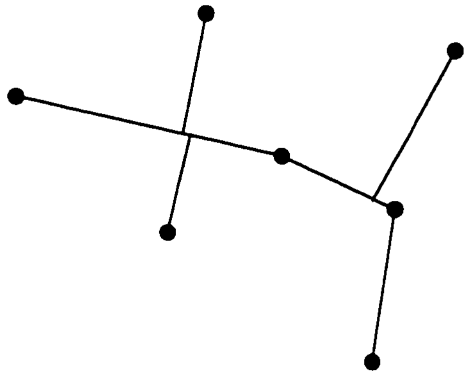


Figure 4.5: Pipeline network schematic

The Manhattan metric describes a system in which, for any given node, the distance to the central facility is farther than the Euclidean metric. Although Fig. 4.4 (b) appears to "share" some network links where overlaps occur on the four axes entering the central facility, the metric actually calculates each "trip" to the central facility separately, so that overlapping distances are counted.

When considering the pipeline network of Fig. 4.5, clearly pipeline links are not duplicated along the same path, and in fact these "overlaps" increase network efficiency as wells, or nodes, share pipelines en route to the central facility. In this way, considering that each node does not require its own dedicated route to the plant and can share routes with other nodes, a shorter average travel distance per node is realized than is even provided by the Euclidean metric. Hence, we would expect an appropriate configuration factor to be something less than its Euclidean counterpart, for a given market shape.

Having stated that the appropriate configuration factor for pipeline networks is based upon neither the Euclidean nor the Manhattan metric, and should measure closer to zero than the smaller of these for a given market shape, it is difficult to determine the exact configuration factor for an optimal gas gathering network.

In order to estimate an appropriate configuration factor for gas pipeline networks, five gas pipeline networks in Alberta were studied. Since we know from Newell (1973) that $kA^{1/2}$ is a measure of the average travel distance to the centroid of an area, k may be revealed by measuring the average travel distance and the production area. These measurements were taken for Amoco's East Crossfield gas plant and gathering system, the side-by-side Gilby plants owned by Gulf and PetroCanada, the Palliser Pipeline Project, Shell Caroline, and Shell Waterton.

It is important to define the area, A, so that the wells are reasonably evenly distributed around the space, in keeping with the uniform density assumption. Large gaps between the well spacing and the area boundary creates a discontinuity of density, implying that the area chosen is too large. The use of real gathering systems to determine k can make the selection of the area boundary difficult, since these real systems don't usually come in shapes that are precisely square, hexagonal or round, and therefore some judgment must be exercised when defining the area.

The case study production areas selected were polygons created by joining the outermost sections containing active wells. The area of the polygons was calculated by adding up the square land sections, or townships depending on the scale, which fell within the boundary. The Shell facilities have a defined "Emergency Planning Zone" which corresponds to the reaction area for any sour gas leaks. This zone was used as the production area for the two Shell facilities studied.

Average travel distance per well should not be taken, in the pipeline network case, to be the average total pipeline distance between the wells and the plant. This is true because when this average distance is multiplied out by the total number of wells, implying the total network distance, shared pipelines are counted more than once. Rather, the average distance per well should be taken as the total network length divided by the total number of wells in the system.

Actual production densities may also be measured for the studied systems, to indicate an appropriate average value for ρ. Total area production can be taken as the plant capacity, since, at the time of construction, it is reasonable to assume that the plant was full, and corresponded to the productivity of the wells in the collection area.

Table 4.2 summarizes the measurements for the gas gathering systems studied, including plant capacity, V, total network length, L, number of wells, n, average travel distance, t, and the production area, A.

Table 4.2: Measured gas plant parameters V, L, n, t and A

Gas Plant	V ($10^6 m^3/d$)	**L (km)**	**n**	t **(km)**	**A (km^2)**
Amoco East Crossfield	3.03	66	22	3	209
Gulf/PetroCan Gilby	2.87	173.7	32	5.4	297
Palliser Pipeline	34.0	952	69	13.8	20,000
Shell Caroline	9.44	78	15	5.2	402
Shell Waterton	13.3	139	65	2.1	562

The following relationship is used to solve for k:

$$k = \frac{t}{A^{1/2}} \qquad (4.13)$$

Eqn. 4.2 shows the relationship used to calculate ρ. Table 4.3 summarizes the calculated configuration factors, k, and production density, ρ, for the systems studied.

Table 4.3: Configuration factors and production density for five Alberta gas pipeline systems

Gas Plant	**k**	ρ **(m/d)**
Amoco East Crossfield	0.21	0.015
Gulf/PetroCanada Gilby	0.32	0.0097
Palliser Pipeline	0.098	0.0017
Shell Caroline	0.26	0.024
Shell Waterton	0.089	0.024
Average of five plants	0.20	0.015

A noteworthy point revealed in Table 4.3 is that there appears to be a broad range of k-factors, even among the five systems analysed. Palliser and Waterton, in particular, have revealed k-factors much lower than the others. This may be attributed in part to the relatively large proportion of "sharing" of pipelines occurring in these two cases, thereby reducing the measured average travel distance to the centroid, or gas plant. In the Waterton case, the density of wells is much higher than in the Caroline case, for instance. In the Palliser case, the long, skinny market area associated with this trunk line design results in the same effect.

It is also true that the selected pipeline systems are sub-optimal, so that revealed configuration factors are higher than they would be for a shorter, optimal network.

However, the variability of the networks, and the subjectivity associated with the choice of production area suggests that the best choice of configuration factor from this small sample for the purposes of this analysis is an average of the five revealed values, or $k_{pipe} = 0.2$. Reasonably, however, given the small sample studied, we may only conclude that for the general case, k_{pipe} is somewhere in the range of 0.1 to 0.3.

Using the following parameters, then, Eqn. 4.12 may be used to determine V^*:

k_{pipe} = 0.2,
ρ = 0.015 m/d,
γ = 6.6×10^{-4} $m^{-4}d^{-1}$,

where γ is based on an industry rule-of-thumb cost of $30,000 per diameter-inch-mile, and three-inch pipe which can carry 85,000 m^3/d (3 mmcf/d).

Solution of Equation 4.12 using these parameters, along with a_{sour} and b_{sour}, yields an optimal sour gas plant size, V^*_{sour}, of 9.9×10^7 m^3/d (3500 mmcf/d).

Similarly, using a_{sweet} and b_{sweet}, the optimal sweet gas plant size, V^*_{sweet}, was calculated to be $2.4 \times 10^7 m^3$/d (850 mmcf/d).

Table 4.4 shows the different solutions obtained by varying k over the established range between 0.1 and 0.3.

Table 4.4: Sensitivity of optimal plant size to k-factor

k	**V^*_{sweet} (10^6 m^3/d)**	**V^*_{sour} (10^6 m^3/d)**
0.1	44	170
0.2	24	99
0.3	17	70

It is clear from Table 4.4 that there is an inverse relationship between the k-factor and V^*, as we should expect. In other words, when k is decreased, V^* increases. Lowering the value of k is akin to decreasing the average travel distance to the centroid. In so doing, we would expect that it would now be more optimal to tie in more nodes, since they are now "closer" to the centroid, and thereby increase the optimal plant capacity. Notably, k has the same effect in Eqn. 4.12 as γ, the unit transport cost. This implies that increasing transport distance, and transport cost per unit distance, have the same effect on V^*. It is also clear that V^*_{sour} is larger than V^*_{sweet}, which is expected since the sour facilities are generally more expensive to build, thereby making longer transport distances more economically attractive than building a second facility.

The average capacity of a gas plant in Alberta was 9.9×10^5 m^3/d (35.1 mmcf/d) in 1994 (Wearmouth, 1994). Clearly, the optimal plant capacities calculated using the market area formulation are much higher than this, by one or two orders of magnitude. This result is interesting and illustrates mathematically that for any gas production field in Alberta, we would expect to only build one processing plant, since Alberta field production sizes are much lower than the values calculated for V^*. In fact, this analysis suggests that multiple plants would only be appropriate for gas production fields of world-class size, and even then would probably be difficult to justify. Hence, the gas pipeline network designer should expend little cognitive energy deciding how many plants are optimal for a given field, and plan to build only one facility.

Clearly, then, one would conclude that Alberta contains far too many gas plants, and the average processing capacity is too low. This result coincides with the regulations of the Alberta Energy and Utilities Board (EUB) which requires, as justification to build a new gas plant, evidence that existing processing facilities were considered and shown to be insufficient in some way. This guideline is referred to as the EUB's Policy on Plant Proliferation (Alberta Energy and Utilities Board, 1991).

An interesting comparison can be made between the outcomes of provincial government policy in each of Alberta and British Columbia. British Columbia is home to only a fraction of the total gas reserves belonging to Alberta, but yet the average gas plant size there is much larger than in Alberta. A local industry expert estimates total BC gas production at present is in the range of 2 bcf/d, and only ten to twelve processing plants exist to handle this production, resulting in an average plant size of about 180 mmcf/d, or 5×10^6 m^3/d. Evidently, BC is home to gas gathering systems which are much closer to the optimal size than in Alberta. A number of factors can be used to explain this phenomenon, such as (1) high proportion of sour gas production in BC encourages lower facility density, (2) higher levels of regulation in BC lower competitive influences, thereby reducing plant proliferation, (3) remote areas allow longer transport distances for dangerous sour gas, and (4) high levels of liquid entrainment (valuable, heavier hydrocarbons) encourage the construction of expensive, deep-cut facilities.

This chapter discusses the important topic of the appropriate number of central facilities, or processing plants, in a simplified gas gathering system. The model results lead to the straight-forward conclusion that, in almost every case, the appropriate number of processing facilities for a gas field is one. While this might be obvious to gas facility designers, it leaves unanswered the question of why Alberta has experienced gas plant proliferation, and has a relatively small average facility size. The answer to this question is sure to be complex, and not necessarily in the sense evaluated here. It is left for the reader to ponder, and industry to address, since there are certainly political, technical, economical and environmental factors involved.

CHAPTER 5

OPTIMAL ROUTING OF PIPELINES

"Perfect speed, my son, is being there."

Chiang to Jonathon
in Richard Bach's *Jonathon Livingston Seagull*,
1970, Avon Books: New York, p. 65.

5.1 Introduction

This chapter analyses the problem of designing the pipeline network itself, growing on the previous chapter which studied the appropriate number of central facilities for a gas producing field. The techniques presented here are useful for generating several alternative systems of near-optimal configuration which can be compared using economic and qualitative metrics, as are commonly applied in industry, to determine the best network layout.

Network design techniques for pipelines are not well documented nor consistently applied in practice. Practical, straight-forward analysis techniques for the generation of alternative network solutions, as presented herein, will provide industry with a guideline for effective pipeline network design. Incorporation of environmental factors in the network design algorithm is also explained. The chapter concludes with a case study of the Amoco East Crossfield gas plant and gathering network.

5.2 Network Techniques for Gas Pipelines

This section reviews the principles of the Minimal Spanning Tree (MST) and the Steiner Minimal Tree (SMT), and extrapolates their theory to the pipeline problem.

5.2.1 Minimal Spanning Tree

Spanning tree is a term used in network theory which describes a complete network connecting a number of nodes and which contains no loops. A minimal spanning tree (MST) is a spanning tree which connects the nodes in such a way as to minimize the total link length. Spanning trees have links which go only between nodes, not through any *imaginary* nodes, and the algorithm does not create new nodes.

The application of minimal spanning trees to the establishment of a gathering pipeline network is obvious since one objective is usually to minimize total link length. The algorithm for finding the minimal spanning tree for a collection of nodes is as follows:

(1) starting from any node, create a link to the next closest node;
(2) create the next link between the closest connected and unconnected nodes;
(3) if any unconnected nodes remain, go back to Step (2).

A minimal spanning tree is a good start towards establishing an optimal gathering pipeline network. However, it has been proven (Du and Hwang, 1992) that up to 13.4 percent improvement over the MST is possible with a Steiner tree. Steiner trees are explained in the next sub-section.

5.2.2 Steiner Trees

A Steiner tree is a network which connects a set of nodes, N, and reduces the total link length with the addition of some additional points, S, called Steiner points. The Steiner minimum tree (SMT) is a Steiner tree with the shortest possible total link length. Chapter 3 contains a discussion of Steiner trees, and an illustration, repeated here, to clarify the concept of the Steiner point.

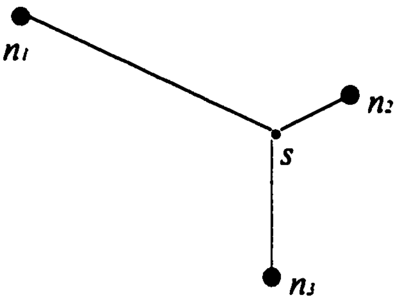
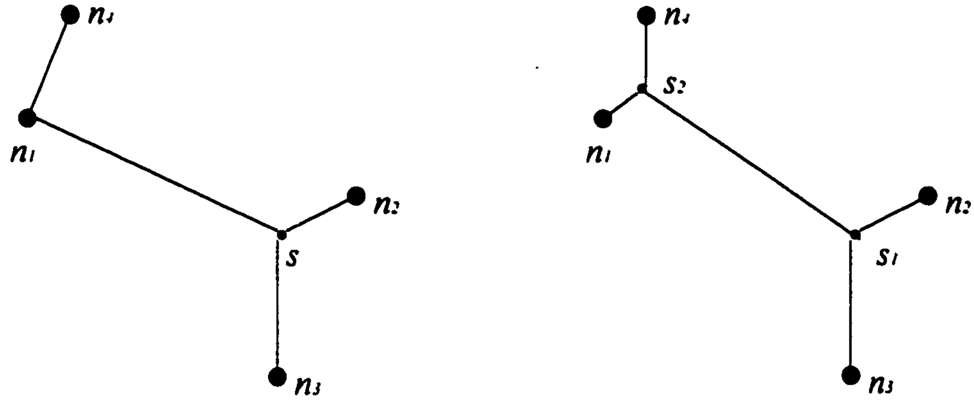


Figure 5.1: Steiner Minimal Tree for three points

Steiner networks which differ only by the number of Steiner points utilized are considered to have differing *topologies*. The shortest Steiner tree, given a certain topology, is considered a relatively minimal Steiner tree. The global Steiner minimum tree, or SMT, is that minimum configuration of the one topology which creates the shortest possible Steiner tree. The SMT is always a full topology, or a tree with n-2 Steiner points, where n is the number of nodes in the network. Figures 5.2(a) and (b) illustrate two topologies for a network of four nodes. Figure 5.2(a) has a topology of one, and Fig. 5.2(b) has a topology of two, which is a full topology for a network of four nodes.

It is important to understand some basic mechanical properties of Steiner minimal trees. Firstly, every angle in the network is at least 120°. Every Steiner point is joined to the network using three lines at angles of 120°. No links cross each other in an optimal Steiner tree. And the maximum number of Steiner points in a

SMT is two fewer than the number of network nodes, corresponding to a full topology.



(a) Topology = 1

(b) Full topology = 2

Figure 5.2: Topologies for a four-node network

A spatially optimal pipeline network would be a SMT connecting all of the wells or facilities in the pipeline problem. In reality, it is unlikely that this spatially optimal solution would be chosen, even if it were easy to determine. This is true because of the existence of environmentally sensitive areas, preferred existing corridors (such as roads or utility corridors) and surface land conditions in the region of the pipeline network which make certain routes undesirable or prohibitively expensive.

Also, as discussed in Chapter 3, Steiner trees are difficult to determine and no suitable algorithm has been found for networks with a large number of nodes. Alternatively, the MST algorithm is very simple and may be used successfully for any number of network nodes. The following sub-section offers techniques for modifying the simple MST network, using knowledge about Steiner trees, to achieve network efficiency improvements.

5.2.3 Steiner Improvements to the MST

In the pipeline industry where there are many factors affecting the choice of routes, with shortest total link length being only one design objective, it is unrealistic to expect to construct SMT pipeline networks. However, understanding the principles of SMT construction which reduce link length enables these to be applied in pipeline network design where appropriate.

The following algorithm incorporates the simple MST structure and the salient design concepts of Steiner trees to produce a practical, step-by-step approach to pipeline network design.

<u>Step 1</u> Create the first link between the two closest nodes.

<u>Step 2</u> Create the next link between the closest unconnected node and the nearest network point (along a link or at a node).

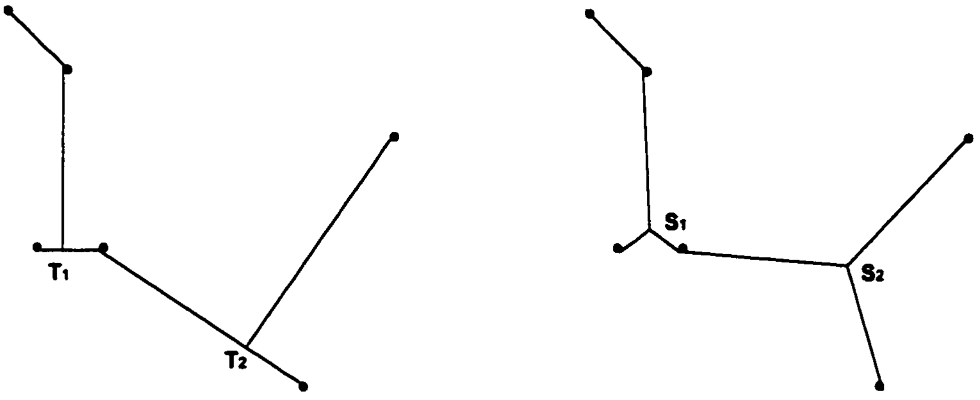
<u>Step 3</u> If any unconnected nodes remain, go back to Step (2).

It should be noted that the result of Steps 1 through 3 can also be achieved by designing a MST without mid-link joins, and then converting node connections which occur at angles of less that 90° into T-junctions. This is the approach employed in the case study to follow.

A network designed using either method is shown in Fig. 5.3 (a). The "T" connections labeled **T_1** and **T_2** are Steiner points which require local optimization. Improving the locations of these T-junctions is the next step in this network optimization process.

<u>Step 4</u> Create an optimal Steiner tree for the given topology by converting the T-junctions to Steiner points at which the links connect at angles of 120°.

The results of Step 4 are illustrated in Fig. 5.3 (b) with S_1 and S_2 marking the two Steiner optimal junctions.



(a) MST with mid-section T-junctions

(b) T-junctions converted to optimal Steiner points.

Figure 5.3: Modified Minimal Spanning Trees

Although relative Steiner minimal trees achieve the shortest network length for a given network topology, these relative minimal trees are not necessarily similar in layout, nor close in total length to the global minimum tree. However, they are an improvement over the MST design, and the concepts are simple to incorporate, unlike an algorithm for determining the SMT.

5.3 Incorporating Environment and Other Factors in Design

Information which is likely to affect pipeline route choices typically takes one of the following two forms: (1) knowledge about regions to be avoided at some cost, or (2) knowledge about regions or corridors which are preferred. Environmental factors typically take the first form, but environmental benefit can also be achieved by sharing rights of way with existing infrastructure, as in the second point. Preferred routes are often existing rights-of-way for pipelines, roads or other infra-structure, or preferred terrain types which promote lower construction costs. Wiechnik et al (1996) is a good example of a pipeline routing problem in which environmental concerns had a huge impact on route selection in an effort to minimize impact in an area of discontinuous permafrost in northern Canada.

The four-step process presented in the previous section does not include a provision for dealing with this kind of information. This section offers additional steps which enable environmental and other route information to become an integral part of the pipeline network design process.

Just as it is important to know the locations of the network nodes which are to be connected, it is equally essential to know the location and layout of environmentally sensitive areas (ESA's), different terrain conditions and preferred routes. Overlaying regions of environmental sensitivity and existing thoroughfares on the graph of network nodes illustrates the interplay between the two systems. Figure 5.4 shows the concept of layering network designs with environmental information. This step is integral in achieving a design which equally accounts for the locations of the nodes and the existence of the surrounding natural environment.

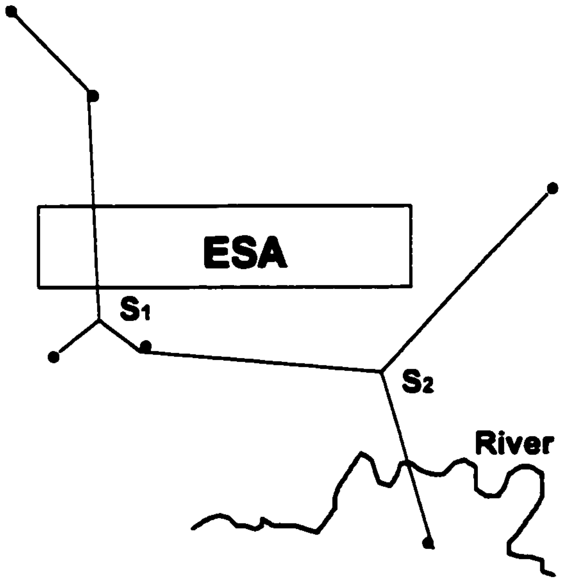


Figure 5.4: Layering network designs with environmental information

The network designed using the four steps of Section 5.3 will now provide the first potential network design. Alternative designs may be created by making adjustments for the environment external to the network itself. Routes around ESA's may be constructed, and routes along preferred rights-of-way incorporated. To achieve spatial optimality two basic principles of the optimal Steiner tree should be observed: (1) All network angles should be at least 120°, where possible, and (2) no link should cross over another.

An alternative design generated using these principles is shown in Figure 5.5. In this figure the alternative network does not change the river crossing point, as a river crossing is inevitable to tie in the last well. However, if certain locations along the length of the river were preferable for a crossing to the one shown, these locations could be investigated using this technique.

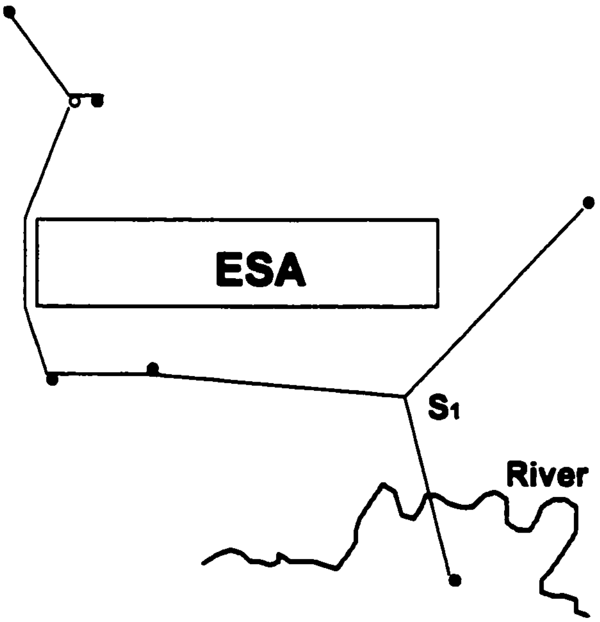


Figure 5.5: Alternative network design taking environment into consideration

Francis and White (1974, pp.12-13) emphasize the importance of generating a large number of alternative solutions, since the best solution will come out of the alternatives generated. It is important to be creative, and they provide a summary of aids to creativity, including "Do not get bogged down in detail too soon," and "avoid premature rejection." Any engineering problem can certainly benefit from sound principles creatively applied.

5.4 East Crossfield Gathering Network

The Amoco Crossfield Gas Plant and gathering network, located near the town of Crossfield, Alberta, north of Calgary, was chosen to illustrate the application of the network design algorithms developed in this chapter. The plant is 3.2 kilometres south of the Crossfield township and processes sour gas. It was designed to process 3.03 x 10^6 cubic metres (107 mmcf) of raw gas per day, and came on stream in February, 1968.

The original construction in 1968 contained 22 wells, connected by a gathering system comprised of approximately 66 km of pipeline. This value was obtained by map measurement as exact figures are difficult to obtain. The analysis done for this work concentrates on these original wells since later field development was unknown at the time the plant and gathering system were built.

The layout of the gathering system, including inter-nodal distances, was taken from a brochure published by Amoco Canada Petroleum Co., titled "Crossfield Plant, August 1993" (1993). The wells and gathering network, along with some important nearby transport facilities, are shown in Figure 5.6. The well numbers are arbitrary and selected for the purposes of this analysis, and will be consistent throughout the remainder of this discussion.

Amoco Crossfield was selected for this analysis for a number of reasons. The evolution of the gas gathering system is nearly complete, as the facility is mature. Thus, it is possible to look back at the stages of the development and discern where benefits might have been achieved with a different layout. Also, the proximity of the plant to Calgary made it easy to visit for the purposes of gathering information.

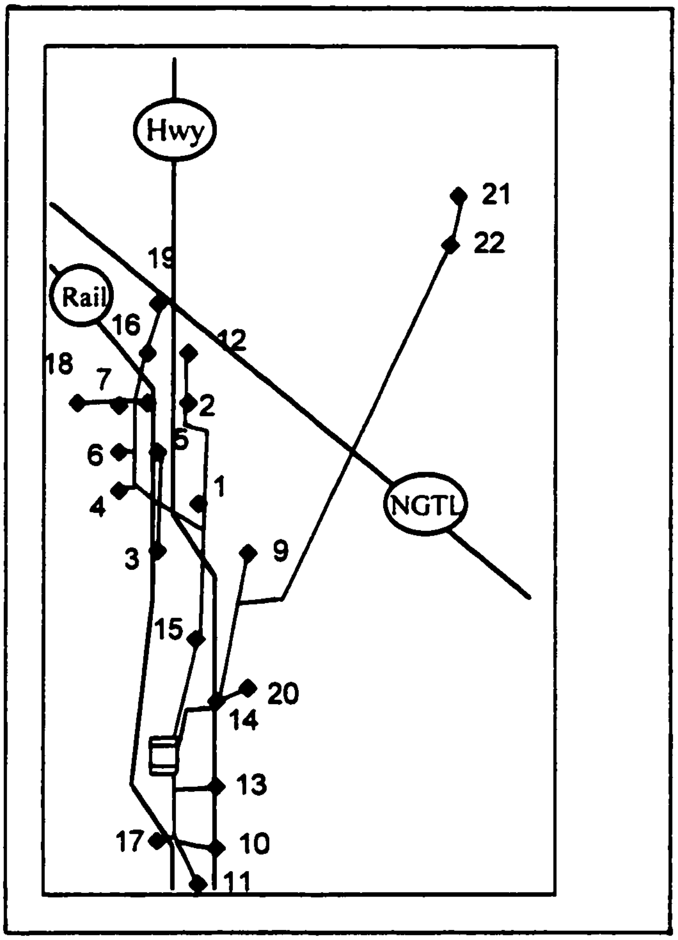


Figure 5.6: Amoco East Crossfield gas gathering system

In order to compare the existing design with the approach presented in this chapter, it was necessary to first establish a MST for the East Crossfield system. A spreadsheet computer program, named haMSTer, was written and used to determine the MST network. The well locations, in degrees of latitude and longitude, fed the haMSTer program, enabling the network design to incorporate the curvature of the earth in its calculations. This MST network is illustrated in Figure 5.7.

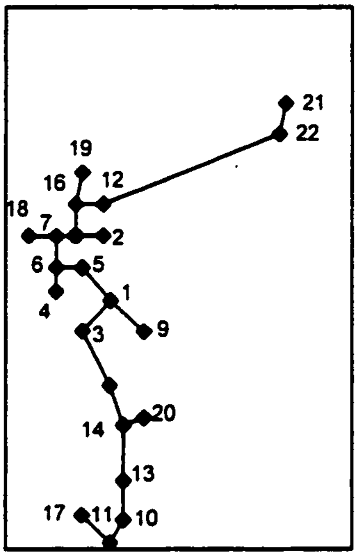


Figure 5.7: MST representation of East Crossfield

The MST calculated required a total link length of 48.9 km, representing a 26% reduction in total network length over actual design.

Following the four-step process detailed earlier requires conversion of node connections which meet at less than 90° into T-junctions. Visual inspection of Fig. 5.4 indicates that two opportunities exist for this improvement: (1) the connection of Node 17 at Node 11, and (2) the connection of Node 19 at Node 16. The T-junction locations on the surface of the earth were determined using the program BISECTOR, described in Appendix B. Completion of these refinements resulted in a pipeline length reduction of only 59 m, less than 1% of the MST network length. This result is not surprising considering the East Crossfield wells are dense and aligned in symmetry with the square legal-land-description system.

Further opportunity exists for improvement at every connection of less than 120°, by incorporation of a Steiner point. Figure 5.7 indicates that ample opportunity for Steiner point optimization exists in this example. A simple geometric calculation indicates that the conversion of a right-angled, three-node network, as in Fig. 5.8(a) can be reduced by 3.41% using a Steiner network, as in Fig. 5.8(b). The network links in similar alignment in the East Crossfield example may not have the identical geometry, but local improvements of around 3% can be expected where the Steiner points are applied.

(a) Right-angled three-point network (b) Steiner three-point network

Figure 5.8: Geometry of Steiner points

CHAPTER 6

CENTRAL FACILITY LOCATION IN A PIPELINE NETWORK

The word "integrity" comes from the verb "to integrate."

from M. S. Peck's *The Different Drum*, 1987,
New York: Touchstone, p. 234.

6.1 Introduction

Where Chapter 4 discussed the optimal number of central facilities in a simplified gas network, this chapter discusses the optimal location of those facilities in a real gas gathering network.

This chapter examines the problem of locating a central facility within an established network system, thus the ideas presented hinge on Hakimi's work on centres and medians, discussed in Chapter 3. This approach is valid because in many cases it is more difficult to optimally design the pipeline network itself, if many terrain and environmental conditions exist, than it is to select a good gas plant location. In the case where the gas plant location choice dominates, it would likely be made using factors quite apart from the future design of the network, such as land cost or availability, proximity to electrical power or other factors which do not affect the pipeline network. This situation is not a topic of this chapter.

6.2 Gas Plants as Medians of Directed Networks

Hakimi's work (1964, 1965) on centres and medians in networks is useful in a discussion of directed pipeline networks, although Hakimi's work focused on undirected networks such as road and communication systems.

A network median is the network node at which the sum of distances, or weighted distances, to all other nodes is a minimum. This differs from a network centre, described as the network point at which the maximum distance to any network node is a minimum. Hakimi relates a network median to the best location for a switching centre in a communications network because it improves the overall efficiency of the system by reducing the average travel distance. A centre is described as the optimal location for a police station because minimizing the longest network travel distance reduces the longest emergency response time, thereby providing a more equal service to residents in the area.

In summary, a centre is the preferred location for a facility which serves people and must do so with a measure of equality. A median may enable higher average service rates, but may also expose a small portion of a network to significantly lower-than-average service rates. This is acceptable where equality of service is non-essential.

It appears, then, that a pipeline-network central facility would be optimal at the network median. The following section presents a method for calculating this median location.

6.3 Determining the Median

Hakimi (1964) defines the term *absolute median* as a median which may be located either at a node or on a network link from which the sum of distances to all other vertices in the network is a minimum. He proves, however, that an absolute median is always located at a node in the network, and thus the median and absolute median are the same.

Hakimi describes the absolute median, y_0, with the following expression:

$$\sum_i h_i d(v_i, y_0) \le \sum_i h_i d(v_i, y) \qquad (6.1)$$

where v_i denotes a vertex or node in the network,
h_i represents the weight associated with vertex v_i,
y implies any vertex other than y_0, and
$d(v,y)$ signifies the network distance between nodes v and y.

A practical and simple method of calculating a network median is done using a distance table. A distance table is a two-dimensional chart which lists all network nodes along both the vertical and horizontal axes. At the intersection of rows and columns headed by the nodes, the table displays the network distance, or weighted network distance, between the nodes represented. In this way, the distance between every pair of nodes in a network may be displayed in a chart which contains rows and columns equal to the total number of nodes in the network. The table column which generates the lowest total corresponds to the network median. This is true since the sum of one column of a distance table is the total distance from the node represented to all other nodes in the network.

Using the simple network shown in Fig. 6.1, Table 6.1 illustrates the distance table method for finding the median of a network. The median of the network examined is located at node D, since the total of column D in the Table 6.1 is the lowest column total.

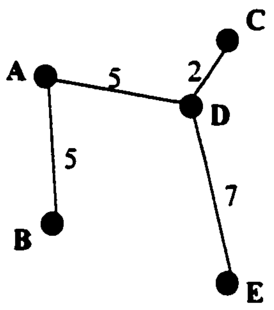


Figure 6.1: Simple network with link distances

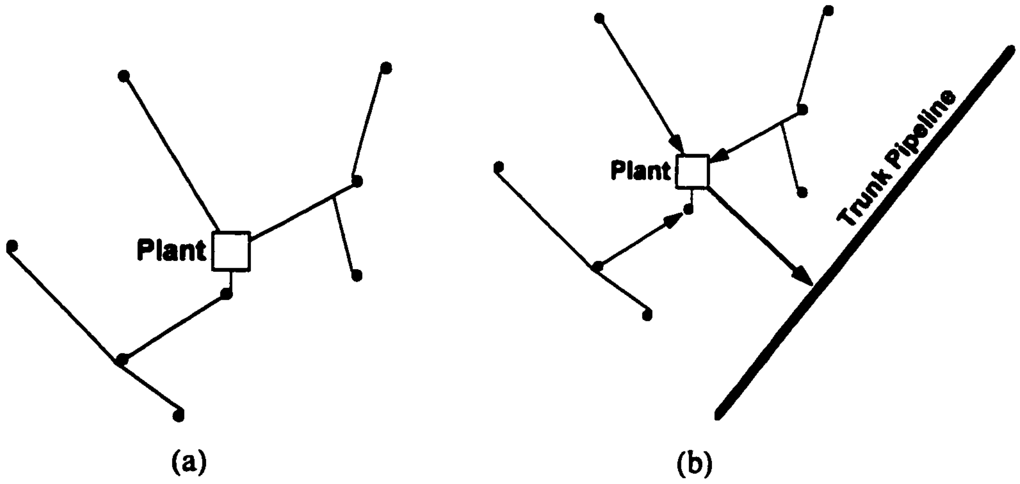
Table 6.1: Distance table for calculating network medians

NODE	A	B	C	D	E
A	0	5	7	5	12
B	5	0	12	10	17
C	7	12	0	2	9
D	5	10	2	0	7
E	12	17	9	7	0
TOTAL	**29**	**43**	**30**	**24**	**45**

6.4 Defining the Gas Pipeline Network

Figure 6.2(a) shows a gathering network with a plant located at the median. Figure 6.2(b) shows the same network with a link connecting the plant to a trunk pipeline. This section describes the application of the median technique to the latter of these network types.

Downstream transportation systems carry processed products to their respective markets. In the case of sales gas, a trunk pipeline moves the purified natural gas to homes and businesses which are, in most cases, far from the plant itself. A pipeline link must connect the plant to these downstream systems, as shown in Fig. 6.2(b). Therefore, the choice of median should account for links to downstream transport systems.



(a) (b)

Figure 6.2: Gathering systems with a downstream trunk pipeline

Network links may be distinguished by their direction of travel. Links which carry gas into the plant are inbound links, and those which ship products out of the plant are outbound links.

The problem under consideration has established inbound links. The outbound links, however, have not been constructed and their routes will tie in to the chosen plant location. The median in this case can be found using a distance table. Inbound link distances are measured along the links of the established gathering network, as described in the previous section. Outbound links, however, are measured as the shortest distance between the node being analyzed and the downstream transportation system. The following example illustrates this method.

Figure 6.3 shows a network with one downstream transportation system, a trunk pipeline. The dashed lines indicate the shortest path between each point in the network and the trunk pipeline, and distances are shown in square brackets.

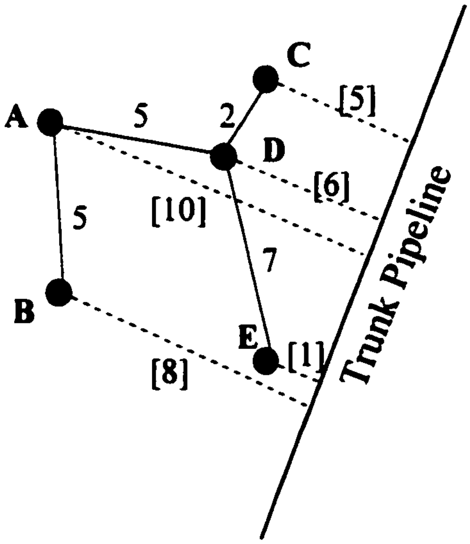


Figure 6.3: Simple network and trunk pipeline

The median can be calculated using the distance table shown in Table 6.2. The table totals indicate that the median location is unchanged, at node D, when the trunk pipeline location is taken into account.

Table 6.2: Distance table for network and downstream trunk pipeline

NODE	A	B	C	D	E
A	0	5	7	5	12
B	5	0	12	10	17
C	7	12	0	2	9
D	5	10	2	0	7
E	12	17	9	7	0
Trunk	10	8	5	6	1
TOTAL	**39**	**51**	**35**	**30**	**46**

Multiple downstream transportation systems could be weighted according to relative cost, since a road, pipeline and rail line, for instance, would have different construction costs per unit distance.

6.5 Case Study of Amoco East Crossfield Gas Plant and Gathering Network

The Amoco East Crossfield gas plant and gathering system were explored in Chapter 5 for the purpose of illustrating the network design techniques developed in that chapter. This chapter revisits the East Crossfield example for the purpose of testing the gas plant location techniques explained in the previous sections on an operational, fully-developed sour-gas gathering system.

Chapter 5 provides a brief history of East Crossfield and a diagram of the field layout in 1968, when production first began. The gas pipeline network at that time tied in 22 producing gas wells using a total distance of 66 km of gathering pipeline.

6.5.1 Overview of the East Crossfield Network

Figure 6.4 illustrates the general layout of wells, plant at Node 23 (marked with a box), and gathering pipelines, and shows the approximate locations of downstream transport systems which are important to the operation of the Amoco Crossfield gas plant. These include Alberta's #2 highway, a main highway route for trucking liquids and sulphur, the NGTL mainline, and the railway also used for hauling sulphur from the plant. Well labels follow the format of Chapter 5.

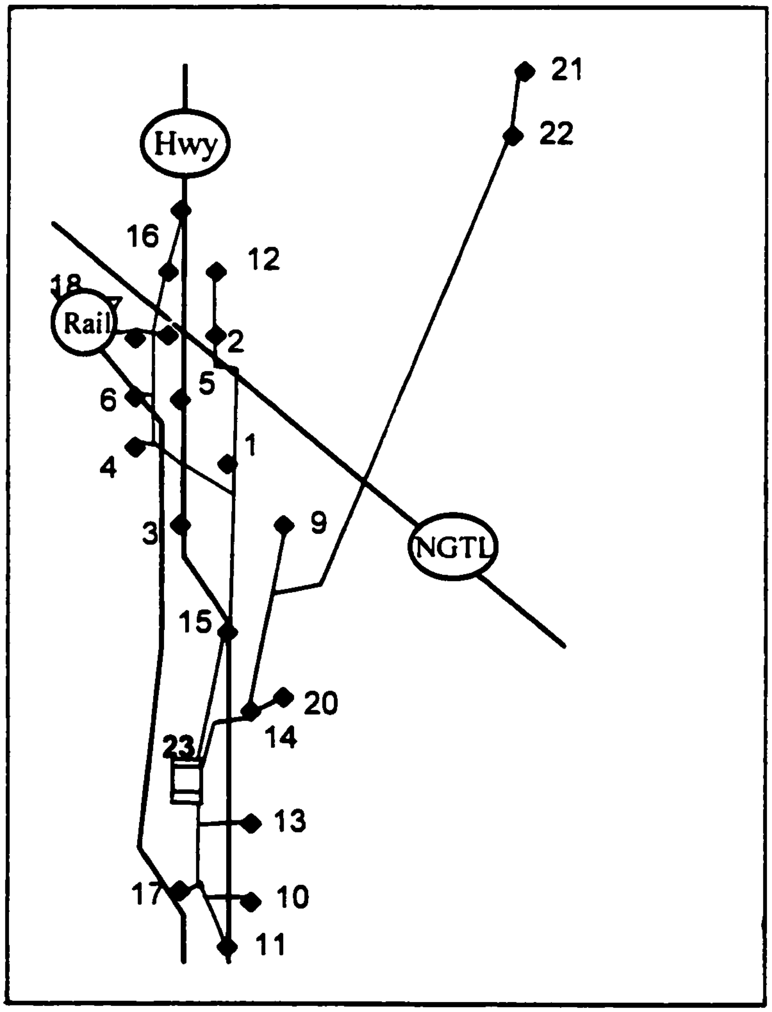


Figure 6.4: Layout of Amoco Crossfield wells, gathering system, plant and downstream facilities

At the time of facility construction, the field was laid out in a north-south fashion, approximately 19 km long and 8 km wide, at the most distant points. The plant was located approximately 5 km north of the southern-most end of the field, and on the western extremity.

6.5.2 Median of East Crossfield

The median location of the gas network, shown in Fig. 6.4, is at Node 15 when downstream transportation systems are not taken into account. The distance chart method was used to determine this location. This distance chart is shown in Table 6.3, with node 23 representing the actual gas plant location. The median is that node which has the lowest column total, excluding distances to downstream systems, and Node 15 is the lowest at 228.6 km.

When the downstream NGTL transmission trunk line, main highway #2 and nearby rail lines are considered in the selection of a median location the optimal location changes. The Grand Total row of Table 5.3 includes the shortest distances from each node to the three downstream systems. When these systems are included in the analysis the best location for a central facility becomes Node 1, with the lowest associated network link distance of 236.7 km. The actual location of the gas plant, at Node 23, is the 4th best pick of all the nodes, and represents only an 8% increase in total distance traveled.

The East Crossfield analysis assumed that links to downstream transport systems could be represented by the perpendicular distance between the node and the trunk pipeline, highway or rail line. This assumption does not account for natural obstructions or ESA's which might result in another route being more realistic. Additionally, this analysis assumes that unit construction costs for all downstream modes, pipeline, road and rail, were the same.

Table 6.3: East Crossfield distance chart. in km

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.0	4.7	6.3	6.8	7.0	8.3	9.6	9.4	7.2	14.3	14.1	6.4	12.2	8.1	5.2	10.8	13.0	11.2	12.5	7.7	23.7	22.0	8.6
2	4.7	0.0	9.8	10.4	10.6	11.8	13.1	13.0	10.7	17.8	17.7	2.1	15.8	11.6	8.7	14.4	16.6	14.8	16.0	11.2	27.2	25.6	12.1
3	6.3	9.8	0.0	3.1	3.3	4.6	6.0	5.9	10.3	17.2	16.8	11.5	14.9	11.3	7.8	7.2	15.6	7.7	8.8	11.6	26.7	25.1	11.3
4	6.8	10.4	3.1	0.0	10.4	2.7	4.4	4.2	10.5	17.4	17.0	12.0	15.1	11.5	8.0	4.6	15.8	5.0	6.3	11.8	26.9	25.2	11.5
5	7.0	10.6	3.3	10.4	0.0	5.4	6.8	6.6	11.1	17.3	17.6	12.2	15.7	12.0	8.6	7.9	16.3	8.4	9.6	12.4	27.5	25.8	12.0
6	8.3	11.8	4.6	2.7	5.4	0.0	3.1	2.9	11.9	18.8	18.4	13.4	16.5	12.9	9.4	4.5	17.2	4.1	6.2	13.2	28.3	26.7	12.9
7	9.6	13.1	6.0	4.4	6.8	3.1	0.0	1.2	13.1	20.1	19.6	14.8	17.7	14.1	10.6	2.5	18.4	1.7	4.1	14.4	29.5	27.9	14.1
8	9.4	13.0	5.9	4.2	6.6	2.9	1.2	0.0	13.0	19.9	19.5	14.6	17.6	13.9	10.5	2.4	18.2	3.0	4.0	14.3	29.4	27.7	13.9
9	7.2	10.7	10.3	10.5	11.1	11.9	13.1	13.0	0.0	13.1	13.0	12.4	11.3	5.8	8.3	14.3	12.0	14.8	15.9	6.4	19.8	18.2	7.7
10	14.3	17.8	17.2	17.4	17.3	18.8	20.1	19.9	13.1	0.0	2.9	19.5	7.2	8.0	8.9	21.2	2.6	21.7	22.9	9.1	29.6	28.0	5.4
11	14.1	17.7	16.8	17.0	17.6	18.4	19.6	19.5	13.0	2.9	0.0	19.3	7.0	7.8	8.7	21.0	2.5	21.3	22.7	8.9	29.5	27.8	5.3
12	6.4	2.1	11.5	12.0	12.2	13.4	14.8	14.6	12.4	19.5	19.3	0.0	17.4	13.3	10.4	16.0	18.2	16.4	17.7	12.9	28.9	27.2	13.8
13	12.2	15.8	14.9	15.1	15.7	16.5	17.7	17.6	11.3	7.2	7.0	17.4	0.0	6.2	7.1	18.9	5.9	19.4	20.5	7.3	28.1	26.5	3.6
14	8.1	11.6	11.3	11.5	12.0	12.9	14.1	13.9	5.8	8.0	7.8	13.3	6.2	0.0	6.0	15.3	6.8	15.8	16.9	1.5	22.2	20.5	2.6
15	5.2	8.7	7.8	8.0	8.6	9.4	10.6	10.5	8.3	8.9	8.7	10.4	7.1	6.0	0.0	11.8	7.8	12.3	13.4	7.2	28.0	26.3	3.5
16	10.8	14.4	7.2	4.6	7.9	4.5	2.5	2.4	14.3	21.2	21.0	16.0	18.9	15.3	11.8	0.0	19.6	4.1	1.7	15.6	30.8	29.0	15.3
17	13.0	16.6	15.6	15.8	16.3	17.2	18.4	18.2	12.0	2.6	2.5	18.2	5.9	6.8	7.8	19.6	0.0	20.1	21.1	7.8	28.3	26.7	4.3
18	11.2	14.8	7.7	5.0	8.4	4.1	1.7	3.0	14.8	21.7	21.3	16.4	19.4	15.8	12.3	4.1	20.1	0.0	5.8	16.1	31.2	29.5	15.8
19	12.5	16.0	8.8	6.3	9.6	6.2	4.1	4.0	15.9	22.9	22.7	17.7	20.5	16.9	13.4	1.7	21.1	5.8	0.0	17.2	32.4	30.7	16.9
20	7.7	11.2	11.6	11.8	12.4	13.2	14.4	14.3	6.4	9.1	8.9	12.9	7.3	1.5	7.2	15.6	7.8	16.1	17.2	0.0	21.0	19.4	3.7
21	23.7	27.2	26.7	26.9	27.5	28.3	29.5	29.4	19.8	29.6	29.5	28.9	28.1	22.2	28.0	30.8	28.3	31.2	32.4	21.0	0.0	1.7	24.5
22	22.0	25.6	25.1	25.2	25.8	26.7	27.9	27.7	18.2	28.0	27.8	27.2	26.5	20.5	26.3	29.0	26.7	29.5	30.7	19.4	1.7	0.0	22.9
23	8.6	12.1	11.3	11.5	12.0	12.9	14.1	13.9	7.7	5.4	5.3	13.8	3.6	2.6	3.5	15.3	4.3	15.8	16.9	3.7	24.5	22.9	0.0
Ntwk Total	**229**	**296**	**243**	**241**	**264**	**253**	**267**	**265**	**260**	**343**	**338**	**330**	**312**	**244**	**229 •**	**289**	**315**	**300**	**323**	**251**	**575**	**540**	**242**

NGTL	4.6	2.6	6.8	6.5	4.5	5.6	4.5	3.6	4.4	12.1	13.7	1.3	10.7	8.6	7.8	2.4	13.6	5.6	1.1	7.5	9.8	8.4	10.7
Hwy	1.1	0.6	1.2	2.2	0.7	2.1	2.2	1.4	2.1	0.2	0.7	0.6	0.2	0.2	0.5	1.0	2.3	3.9	0.7	1.4	11.4	11.1	1.7
Rail	2.1	1.2	0.3	1.3	0.2	1.3	1.6	0.3	3.4	2.1	1.0	1.7	2.7	2.7	1.6	0.3	0.2	2.8	1.7	3.7	13.6	12.6	1.4
Grnd Total	**237 ***	**300**	**251**	**251**	**270**	**262**	**275**	**270**	**270**	**357**	**354**	**334**	**326**	**256**	**238**	**293**	**331**	**312**	**327**	**263**	**610**	**572**	**255**

Were we to incorporate factors to represent the relative construction cost of the alternative transport systems, a more accurate result can be determined. Using the approximation of pipeline construction costs at $30,000 per diameter-inch-mile, and an 8-inch sales gas pipeline, the unit cost is $150,000 per kilometre ($240,000 per mile).

A discussion with engineer Danny Wong of the Department of Engineering Services - Prairie District at Canadian Pacific Railway revealed a rule-of-thumb cost for a private siding installation with two turn-outs, including labour, materials and sub-grade, is around $500,000 per kilometre ($800,000 per mile).

A telephone conversation with Frederick Lee, an engineer with Alberta Transportation and Utilities, provided a rough cost estimate for a graded, graveled, paved 2-lane highway is approximately $400,000 per kilometre ($640,000 per mile).

Using the mode weighting factors, m, of m=1 for pipelines, m=2.7 for highways, and m=3.3 for rail lines, the median was re-calculated. The new median falls at Node 15. Interestingly, when weighting factors are taken into account, the median is the same as when no downstream systems are considered. Node 15 is located right on the #2 highway, the same distance from the rail line as Node 1, and farther from the NGTL mainline that Node 1. It appears that distance to the main pipeline was traded off against proximity to the highway.

CHAPTER 7

ENVIRONMENTAL VALUE REVEALED BY PIPELINES

The best news for the environment is the growing recognition that
decency can be profitable - and increasingly (we hope)
tax-deductible.

from Faith Popcorn's *The Popcorn Report*, 1992,
New York: HarperCollins, p. 87.

7.1 Introduction

Examples of environmental damage potentially caused by pipelines include disturbance of soil, forest, rivers and wetlands, noise from compressor stations or during pipeline discharge, and risk of pipeline leakage or rupture. Environmental valuation is a method by which monetary values are placed upon environmental attributes, which enables these attributes and associated damage or risk, to be included in project cost-benefit analysis. This chapter discusses the concept of environmental value and how it is determined, and then proposed a method for using the optimisation techniques developed herein for revealing environmental value. The chapter concludes by using the Palliser Pipeline Project to illustrate the concepts described.

7.2 Environmental Values as an Aid to Decision-Making

Placing any kind of value on the environment is a difficult thing to do. This is true with almost all "public goods". A public good is something to which everyone has the same level of access and which is not paid for in the same fashion as private goods, such as automobiles and microwave ovens. Clean air, beautiful views and quietness may all be considered to be public goods. The concepts discussed in this chapter have been extensively applied in recent years amongst researchers and academics looking for new ways to approach environmental problems, and these concepts are discussed in detail in Dott et al (1996b). Their applicability in industry has been limited, as will be shown, because of practical difficulties associated with some of the valuation methods. In addition, researchers have found widely varying results for different studies, making the "correct" value difficult to determine.

Standard cost-benefit analysis weighs the costs and benefits of a proposed project, almost always in monetary terms. Usually the project with the highest net present value (NPV), or time-adjusted net benefit, is the one which is pursued. Using valuation techniques, environmental costs can be added into the cost-benefit analysis, forming one of the project costs.

An example of a case where environmental costs could be used at the project planning stage is in an economic comparison of two or more alternative project scenarios. The first scenario might have a shortest link-length pipeline network connecting a number of wells to a gas processing plant, for example. This scenario could represent the cost-optimal pipeline network if environmental costs were insignificant or ignored. The second scenario uses the first scenario as a base, but re-directs some links around environmentally sensitive areas (ESAs), such as wetlands or river crossings, resulting in a longer total pipeline length. The first scenario would include as its costs two main things: (1) the cost of constructing the pipeline, and (2) the cost associated with the environmental damage incurred. The second scenario would have only one main cost item, that being the construction cost of the longer pipeline network.

It is true that neither of the two options described above avoid environmental degradation entirely, but a comparison of the two will indicate the preferred route. If society values wetlands and rivers, in this example, sufficiently highly to justify a longer pipeline route to avoid their damage, then the second scenario would be chosen. Environmental values used in a similar fashion could indicate "go" or "no-go" status on projects when the environmental damage incurred by the project, in any form, has a greater value than the expected benefits of the project.

As expressed by Zube (1980), information on the value of the environment can also be helpful for governmental agencies in setting policy and direction for spending on our environment, property zoning and development planning, to name a few areas.

People may have difficulty placing monetary value on environmental goods, because it is an unfamiliar task; however, when decisions are made which affect the environment, as they are every day by development professionals, values are automatically implied in those decisions. For example, while it is difficult for people to place a value on human life, these values are inferred all the time by engineers who understand that some risk of death or injury are associated with their designs, as much as we try to minimise them. There is some risk of automobile accident at urban road intersections, and the robustness of the design is always weighed against the risk of death or injury, thereby inferring a value on human life.

7.3 Monetary Valuation Techniques

Pearce (1993) describes three general types of monetary valuation techniques for environmental goods: the household production function (HPF), hedonic price methods (HPM), and experimental methods. The first two methods rely on values that are revealed through actual behavior. The third technique, experiment, uses surveys which ask people what values they place on the goods. Each of these methods is described further in the following sub-sections.

7.3.1 Household Production Functions

The HPF method takes expenses which serve as substitutes or complements for an environmental good as the value of that environmental good. The travel cost method, which came into common use in 1966 (Cummings et al., 1986), is based on this concept. The travel cost method recognizes that travel is a complement to experiencing, for example, recreation benefits at a distant site. Using this method, the minimum value of the recreational benefit would be approximated using the cost of travel to the site.

7.3.2 Hedonic Price Method

While the HPF method uses explicit costs to estimate value, the HPM looks at implicit pricing in markets where the environmental good is traded. For example, beautiful surroundings are traded in the real estate market. By analyzing prices for property with beautiful views against property prices without those views it is possible to determine the value placed on a beautiful view by people. HPM was introduced in 1974 by Rosen (Cummings et al., 1986).

HPM may also be described as a revealed preference (RP) technique. RP methods infer value by determining the amount paid for it through indirect measures. For instance, an RP study might infer the value of peace and quiet by studying the range of prices paid for homes located close to and far from airports. RP studies are typically data intensive and have difficulty isolating factors in their analysis.

7.3.3 Experimental Methods

Only experimental techniques can account for the value placed on environmental goods by non-users. For instance, simply because a person expects never to visit

Banff National Park in their lifetime does not mean that they place zero value on it.

Experimental survey methods can be used to determine these kinds of value in two different ways. The first elicits values directly from survey participants by asking them how they value a good. The contingent valuation method (CVM) subscribes to this technique. The second method collects rankings from participants and then ties these rankings to some market value in order to infer value. Surveys which ask for rankings are called stated preference (SP) experiments, or, sometimes, the contingent ranking method. The following section highlights the experimental techniques, discussing their benefits and short-falls.

7.3.3.1 Contingent Valuation Method

CVM uses the principle that a good has a value equal to what it would receive in the marketplace. At different times in history goods may have different values than at others. During a streak of very hot weather air conditioning has a higher value than it does when the weather is cold, for example. It is also true that the value of environmental goods may fluctuate over time, possibly due to the level of environmental awareness, the state of the economy, or the occurrence of environmental disasters. This fact, however, does not detract from the basic principle that the value of a good is equal to what people will pay for it.

CVM constructs a hypothetical scenario in which people may determine and state directly their willingness to pay (WTP) for improvements in the environment, or their willingness to accept (WTA) decreased levels of environmental quality. To ensure that survey respondents state more than just any amount of money they are willing to pay or accept, surveys are designed to determine maximum WTP or minimum WTA. Auctioning can be used to achieve these levels through exercise of the iterative bidding technique. Using this method, after the survey participant states their bid, the surveyor asks them if they would be willing to pay an increment higher, or an increment lower in the case of WTA. This process is repeated until the survey participant will not increase their bid further. The maximum WTP (or minimum WTA) should reveal the value at which the bidder is indifferent to having the money or having the environmental good presented.

7.3.3.2 Stated Preference Techniques

SP methods determine the value of non-market goods indirectly. Rather than have people state a value they would be willing to pay or accept, the technique has people rank alternative "bundles of goods" in their order of preference. The order in which bundles of goods are ranked can be used to show the relative value of each item in the bundle, if sufficient surveys are completed.

SP techniques are based upon the assumption that an individual's selection process amongst a set of alternatives will always seek to maximize their utility, called utility theory. The common, linear utility model is given here for alternative i, or one bundle of goods.

$$U_i = b_1 X_{1i} + b_2 X_{2i} + \dots + b_n X_{ni} \tag{7.1}$$

where i = index representing an alternative,

U_i = utility associated with alternative i,

n = index representing an attribute, and

X_{ni} = attribute n of alternative i being considered.

The SP survey technique collects preference data which is fitted to a form of Eqn. 7.1. The values of b_n reflect the degree to which attribute n influences an individual's level of overall utility. Comparing b_n values amongst the attributes tested reveals trade-off rates between the attributes. If one attribute is money, or a monetary measure of some other attribute such as housing price, then trade-off rates between non-monetary and monetary attributes can be inferred. In this way monetary values for public goods, or otherwise non-market goods, may be determined.

Many of the criticisms of the CVM technique, discussed in the next section, are circumvented using SP methods.

7.4 Critique of Valuation Techniques

The bulk of common criticisms of environmental valuation methods have to do with their hypothetical nature which gives respondents an opportunity to strategize their responses in order to benefit themselves. Much has been done to study survey characteristics which minimize such tendencies, but still the technique receives criticism. This section provides a brief overview of common criticisms of CVM, and their relevance to SP methods.

7.4.1 Strategic Bias

Strategic bias refers to the influence of game-playing by survey respondents. The argument that CVM bid values will be higher for respondents who pay with hypothetical money than for those who actually pay argues for the existence of one form of strategic bias. Here, respondents strategize that they can bid higher to drive up the mean value without actually having to pay. This strategic behavior is also referred to as “free-rider” (Cummings et al., 1986, p. 23) behavior. Other strategic behaviors might include over-statement or under-statement of bids in order to affect the average bid in their favor. Rowe et al. (1980, in Cummings et al., 1986) tested for this by classifying survey participants as varying degrees of "conservationist" and "developer," and testing for strategic bias among responses. Strategic bias was not proven in the data collected using these divisions.

SP respondents are less likely than CVM respondents to succumb to strategic behavior because ranking alternatives which contain a complex bundle of goods is more difficult. The level of intellectual energy required to strategize consistently in this environment would be prohibitive for most participants.

7.4.2 Starting-Point Bias

Another common concern regarding survey design is the existence of starting-point bias. In some CVM studies the survey or interviewer provides the respondent with a starting bid, thereby sending a signal to the interviewee of an acceptable and expected range of bid values. Starting bids are often used in iterative bidding processes which are designed to elicit the maximum willingness to pay.

Survey designers have attempted to avoid starting-point bias in several ways. One way is through the use of a "payment card" (Schulze et al., 1983, and Mitchell and Carson, 1981 in Cummings et al., 1986, p. 37) which contains a large range of possible bids, from which the respondent chooses his or her own starting bid. Other methods provide different starting points to different participants in order to minimize the impact of starting-point bias.

Since SP methods do not require a bid value, but rather ask respondents only to rank alternatives in their order of preference, starting-point bias is not a concern.

7.4.3 Vehicle Bias

Vehicle bias regards an influence on the bid value due to the method of payment of that bid value. For example, if survey participants are told that they would pay their bid value through provincial or state tax increases, respondents who thought taxes were already too high might lower their bid because it would increase their taxes. Other common payment vehicles used in CVM studies include payroll deduction, adders to utility bills, sales tax and consumer product price increases. In order to avoid vehicle bias, survey designers might allow respondents to select their own payment vehicle.

SP techniques are subject to this criticism as well since survey respondents may be asked to consider a certain payment vehicle when formulating their responses.

7.4.4 Information Bias

Information bias refers to the influence on bids which is caused by the provision of differing amounts of information to respondents. Information bias can make interpretation of valuation study results difficult, especially when comparing results from different researchers, as is done in the next section of this chapter.

Madariaga and McConnell (1987) illustrated the existence of information bias in their CVM study of water quality in the Chesapeake Bay. They asked survey participants whether or not they would prefer a beach clean-up project be undertaken in the Bay where, currently, water quality was below a "swimmable" level. Four scenarios were then proposed, the first of which provided no more information, the second told them that even if the water quality was increased public access would be denied, the third told them that taxes would be increased so much in order to pay for the project that nearly all taxpayers would be opposed to the project, and, finally, it was revealed that if the clean-up was not done, the same funds would be used for hospital improvements. In every case, the proportion of "yes" responses was different, indicating the existence of an information bias.

Both CVM and SP researchers must take care to ensure clear, consistent communication of the survey background information. As environmental valuation studies become more widely recognized and conducted, it will become more important to standardize testing techniques in order that results from many different researchers are comparable.

7.4.5 Embedding

Kahneman and Knetsch (1992) discuss what they call an embedding effect which causes goods to be valued lower if they are taken as part of a group, rather than evaluated on their own. The example given from their own research was that Toronto residents were willing to pay only slightly more to prevent dropping fish populations in the whole province of Ontario than they were to prevent the same trend in the Muskoka area, a very small area of the province. This effect creates problems with interpretation of results because "if the value of a [good] is much larger when it is evaluated on its own that (sic) when it is evaluated as part of a more inclusive package of public goods, which measure is the correct one?" (Kahneman and Knetsch, 1992, p. 59). The pair of researchers believe that WTP values are not a representation of people's perceived value of the subject good, but rather represent a purchase of "moral satisfaction." Kahneman and Knetsch even correlate satisfaction ratings with actual WTP values, concluding that WTP values may be predicted using moral satisfaction ratings.

Embedding is equally a concern for both CVM and SP researchers since the effect has to do with the scope of the attribute being valued. This effect is not easily eliminated, but standardization of testing techniques may at least allow valuation research done by different researchers to be compared.

7.4.6 WTP vs. WTA

A complaint about CVM studies is the well-documented difference which exists between people's willingness to pay for improvements in environmental conditions and their willingness to accept degradation in the same environment. Typically, WTP estimates are much lower than WTA values.

The two methods imply responsibility in different ways. Specifically, the WTP method implies that it is the responsibility of the general public to maintain environmental quality of a certain level. On the other hand, WTA measures imply that it is the responsibility of the offending party to compensate the public for their misuse of the environment. Certainly, the two measures may be applied to their appropriate contextual situations, but which represents the real value of the environmental properties being measured? Since SP methods do not require the distinction between WTP and WTA, the issue of the proper measure falls away.

7.5 **Environmental Valuation Research and Results**

This section presents research results from several studies which value environmental attributes relevant to pipeline developments, including visibility/aesthetics of the natural environment, wetland environments, and wilderness (referring to the natural environment people have become familiar with through parks, camping, hiking, etceteras). This brief summary of research results is for the purpose of illustrating the techniques and criticisms presented in the previous two sections, and to ground the reader by establishing a range of monetary environmental values.

The research done in three areas of interest spans over two decades, only a sample of which is presented here, in Table 7.1. Monetary values are presented in 1994 dollars, determined using the GDP deflator, published in Abel et al. (1995). The reported studies use different valuation techniques, as stated in the discussion following Table 7.1.

Table 7.1: Summary of literature on environmental value

Attribute	**Researcher(s)**	**Value (1994 dollars)**
VISIBILITY	Randall et al, 1974	$175-298 per year, per household
	Brookshire et al, 1976	$85 per year, per household
	Rowe et al, 1980	$100-194 per year, per household
	Brookshire et al, 1985	$93 per year, per household
	Patterson, 1995	$25-276 per bad day of air quality, per person
WETLAND	Costanza et al, 1989	$12216 per acre
	Hammack and Brown, 1974	> $95 per acre
	Thibodeau and Ostro, 1981	$506268 - 624544 per acre
	Bergstrom et al, 1990	$109 per acre (recreation value only)
WILDERNESS	Walsh et al, 1984	$48 - 79 per person
	Englin and Mendelsohn, 1991	$719 per trip
	Krutilla and Fisher, 1985	$346 per acre, ($538 with added amenities)

7.5.1 Visibility

The visibility studies reviewed show widely varying results; however, they do indicate that the households interviewed are willing to pay at least $85 per year for substantial visibility improvements (25 to 75 miles) in remote/wilderness areas (Randall et al, 1974, Brookshire et al, 1976 and Rowe et al, 1980). Research in Los Angeles (Brookshire et al, 1985) and Calgary (Patterson, 1995) indicates a comparable value per household, but a larger aggregate since the number of households affected is much greater.

The big question involves the aggregate value of visibility in these cases. The average household may be willing to pay $85 per year, but how many households does this include? All households in the affected province or state? All in the country? Or all in the immediate region? The answer to this question obviously has huge implications for the resultant aggregate valuation. If the affected area, meaning that group of people willing to pay to avoid damage, includes 200 000 households then the aggregate value of visibility at $85 per year per household would be $17 million per year. This number of households corresponds to an urban center with a population of 600 000 people. If 700 000 households were used, representing a population of two million, the aggregate value jumps to $60 million per year.

Even much smaller estimates of the affected population would contribute to a large aggregate value on visibility, having an enormous impact on project development if the costs were acknowledged. Considering that $85 per year per household was the reasonable *minimum* value obtained by the studies, visibility appears to have high value as an environmental good.

7.5.2 Wetland

A second environmental "commodity" examined by researchers and presented in Table 7.1 is wetland. The four research studies presented approached the valuation differently and have widely varying results. Two of the studies (Costanza et al, 1989 and Thibodeau and Ostro, 1981) recognize the value of wetland to encompass more than just recreation, and include storm/flood protection, commercial value, pollution control and water supply as some other sources of value. Their studies used hedonic methods and, therefore, report a kind of aggregate value, per acre. Hammack and Brown (1974) and Bergstrom et al (1984) only include recreation value in their estimates. Overall, the values in Table 7.1 give little indication of a representative value of wetland because of the wide range of values. Evidently, more research needs to be done in this area.

7.5.3 Wilderness

Three research studies which attempted to place a value on wilderness are presented in Table 7.1, each of which used a different valuation method. Walsh et al. (1984) utilized a CVM mail survey to collect their data. The mail survey does not allow the process of iterative bidding since the surveyor is not present when the respondents state their bids. This condition may lower the average bid since some researchers believe that iterative bidding increases the average bid to their maximum value (Cummings et al., 1986, pp. 37-38). However, Bishop and Heberlein disagree, saying that "the process of iterative bidding ... caused people to bid money that they would not bid if the money was [sic] real" (Bishop and Heberlein, in Cummings et al., 1986, p. 137). The fact that Walsh et al. (1984) determined values on wilderness recreation which were an order of magnitude lower than those values determined by Krutilla and Fisher, and Englin and Mendelsohn favors the existence of upward pressure by iteration of bids. Krutilla and Fisher (1985) used an empirical formula developed by Cicchetti and Smith (1973) to determine their values. Englin and Mendelsohn (1991) used a hedonic technique based on travel trips.

The lack of consistent valuation procedures among the wilderness researchers and the small number of studies reported make it difficult, again, to extrapolate useful results for application in an industrial project decision. Once again, it is clear that more research is required to have any level of confidence in applying values.

7.5.4 Comparison of Visibility, Wetland and Wilderness

Respecting the shortcomings of the data presented in Table 7.1, a comparison of the three environmental attributes overall is possible. The general trend of values indicates that wetlands are valued the highest, followed by wilderness, followed by visibility. It seems that wetland may be valued most highly because of commercial and damage prevention attributes which receive attention using the hedonic approach. Wilderness is a broad term which may, for many survey respondents, include a measure of visibility as one of its smaller components. This relationship might partially explain the lower values placed on visibility alone, an example of the embedding effect.

A possible interpretation of the data in Table 7.1 might be that the natural environment is more valuable monetarily when it provides human "services" in addition to universal environmental goods. For example, wetland is attributed much of its value through flood control, pollution control and water supply capacities. Similar human services are not provided, or at least are not measured, in the studies of wilderness. As well, Brookshire et al. (1985) extracted comparatively high bids for visibility in Los Angeles when they associated cleaner air with health benefits, a service provided by this environmental good.

Degradation of the natural environment could contribute to the diminishing of many other similar human services, some of which might result in hearing loss, increased stress levels, higher risk of injury or death in general, soil erosion, insect control or property damage resulting from atmospheric pollution effects like acid rain and smog. With limited information about the monetary value of environment, ranking of more and less valuable environments might be done using the number and value of such services as a guide.

Overall, it is clear that more research needs to be done to determine reasonable values for environmental damage caused by pipelines, petroleum exploration and production, storage facilities and other petroleum-industry development projects. In addition, standardization of measurement attributes would improve comparability across studies. Future research must measure the effects of common environmental concerns in the industry, including greenhouse gas emission, pipeline spills, and destruction or degradation of various ecosystems such as forest, wetland, prairie, streams and montaine regions.

7.6 The Palliser Pipeline Project

The intent of this section is to illustrate a revealed preference technique for establishing an upper bound on the environmental value of a pipeline corridor. The technique is based on the fact that, for a number of reasons, real pipeline networks are not identical to the spatially optimal network for the same nodes. While the author argues that it is constructive to know what the spatially optimal network structure is, there is always non-spatial information which must be accounted for in the final design, such as environmentally sensitive areas, existing developments, terrain conditions, political barriers, and operational considerations. The technique proposes the difference in construction cost between the spatially optimal and actual pipeline route designs represents an upper bound on the revealed value of the affected environment.

The techniques described in the previous chapters are used here to establish an alternative to the planned Palliser system. The concept of a mainline with laterals is abandoned, and the MST concept applied. The Palliser design and MST design are compared and the difference in length is assigned a monetary value, proportionate to the estimated total construction cost. The value of this difference may be considered the upper bound of the revealed environmental value to the designers of Palliser Pipeline.

7.6.1 Overview of Palliser Pipeline Project

The Palliser Pipeline is a natural gas trunk line project which was planned for transporting sales gas from Southeastern Alberta to the Empress/McNeill export location on the Alberta/Saskatchewan border. From Empress/McNeill gas travels via downstream TransCanada Pipeline and Foothills PipeLines to consumers all over North America. This competitive project was undertaken jointly by PanCanadian Petroleum Ltd. and Westcoast Gas Services Inc. and was scheduled to begin operating in the summer of 1998, but stalled at the regulatory application stage as a result of NGTL concessions with Palliser in December of 1996.

The author has received permission to print information pertaining to facility location and layout, and the gross design capacity of 34 x 10^6 m^3/d (1.2 BCF/d).

The plans, as presented in the Application to the National Energy Board (Palliser Pipeline Inc., 1996), were to connect 68 gas processing plants and compressor stations using 709 km of laterals to a mainline of approximately 243 km in length, for a total of about 952 km of installed pipe and a cost of $365 million. The mainline route nearly mirrors the NOVA mainline in the same area, reportedly for environmental reasons. This choice allows simpler access because a corridor is already established; however, it is not understood whether or not Palliser would have direct access to the existing right-of-way, owned by competitor NGTL.

7.6.2 Palliser Pipeline Route Analysis

Table 7.2 lists the names, locations and code numbers used for identification in the analysis of the Palliser Pipeline route.

Table 7.2: Palliser Pipeline node summary

	Node Name	Longitude (Degrees)	Latitude (Degrees)
1	McNeill Delivery Point	110.1398000	50.7170000
2	Hilda West	110.1050000	50.5700000
3	Medicine Hat North	110.1950000	50.4583333
4	Schuler	110.2283333	50.3983333
5	Medicine Hat SW	110.2583333	50.3266667
6	Koomati	110.5050000	50.3916667
7	Bowmanton	110.5050000	50.3083333
8	Bowmanton West	110.5916667	50.2933333
9	Radcliff	110.6100000	50.2200000
10	AECO "E"	110.7633333	50.2216667
11	AECO "D"	111.0350000	50.2200000
12	Suffield	111.0533333	50.1883333
13	Suffield West	111.0533333	50.1666667
14	Medicine Hat East	110.1216667	50.3366667
15	Sask. "A"	109.9250000	50.3133333
16	Sask. "B"	109.8400000	50.2216667
17	Sask. "C"	109.7600000	50.2550000
18	Sask. "D"	109.7783333	50.1800000
19	Sask. "E"	109.9133333	50.1950000
20	Sask. "F"	109.8966667	50.0783333
21	AECO "H"	110.4783333	50.7000000
22	Atlee Buffalo E.	110.4866667	50.7050000
23	AECO "A"	111.0533333	50.7050000
24	Atlee Buffalo S.	110.8150000	50.7100000
25	AECO "B"	111.0233333	50.7050000
26	Jenner West	111.1550000	50.7483333
27	AECO "C"	111.1783333	50.5733333
28	AECO "I"	111.1766667	50.4816667
29	Tide Lake North	111.2883333	50.6283333
30	Tide Lake East	111.2783333	50.5666667
31	Tide Lake	111.2850000	50.5116667
32	Princess #2	111.3233333	50.6933333
33	Iddesleigh	111.4100000	50.6600000
34	Louisiana Lake	111.4533333	50.4866667
35	Alderson S&W	111.4783333	50.2950000
36	12 Mile Coulee	111.0416667	50.0550000
37	Princess South	111.5933333	50.6716667
38	Bantry N.E.	111.7616667	50.6766667
39	Verger Millicent	111.7716667	50.7850000
40	Patricia West	111.6933333	50.8100000
41	Gregory N.E.	111.7383333	50.8950000
42	Cessford	111.6400000	51.0250000
43	Verger	111.9000000	50.8050000

Table 7.2 (continued): Palliser Pipeline node summary

	Node Name	**Longitude (Degrees)**	**Latitude (Degrees)**
44	Matzhiwin South	111.9350000	50.8733333
45	Countess West	112.1016667	50.7016667
46	Cassils	111.9700000	50.6316667
47	Countess South	112.0283333	50.5416667
48	Rainier South	112.0066667	50.2816667
49	Rosemary	112.0150000	50.7966667
50	Rosemary North	112.0316667	50.8616667
51	Gem South	112.0316667	50.8950000
52	Gem West	112.2383333	50.9816667
53	Gem North	112.2166667	51.0366667
54	Bassano South	112.4533333	50.8433333
55	Countess Makepeace	112.4483333	50.9150000
56	Makepeace North	112.4600000	50.9983333
57	Wintering Hills	112.3550000	51.1283333
58	Standard	113.0883333	51.0216667
59	Cavalier	113.1700000	51.0066667
60	Hussar Chancellor	112.8150000	51.0933333
61	Seiu	112.5300000	51.2100000
62	Wayne Dallum	112.6500000	51.3050000
63	Wayne North	112.7666667	51.3666667
64	Nightingale	113.1983333	51.2650000
65	Atusis	113.0200000	51.3600000
66	Carbon	113.0483333	51.4800000
67	West Carbon	113.0083333	51.5200000
68	Ghostpine	112.8650000	51.6316667
69	East Calgary	113.9300000	51.1933333

The haMSTer program was used to create a MST from the nodes listed in Table 7.2. The Palliser gas plants can be divided into two sets of spatially-separated nodes, clearly removed from one another by a relatively large distance. For this reason, and to accommodate the maximum capacity of haMSTer, 50 nodes, the data was divided at an obvious division point for MST calculation purposes, and then re-combined at McNeill to create a total structure.

7.6.3 Environmental Value Revealed by Route Decisions

The MST created by haMSTer using the Palliser Pipeline gas plant locations was 832 km in length. This compares to a Palliser design length of 952 km, for a 13% total length reduction. The construction cost which corresponds to this 13% reduction may be approximated as 13% of $365 million, or $46 million. If we assume that Palliser Pipeline chose a longer and more expensive pipeline design at least partially for the reason of avoiding environmental damage, then the $46 million represents the upper bound of the revealed value of the environment in the region of the pipeline route. Across the 832-km design, this upper bound measured on a distance-unit basis is $55,000 per km.

Earlier chapters indicate that the MST does not represent the shortest possible network, and up to a further 13.4% reduction may be achieved with a Steiner tree. Greater accuracy in the revealed value of the environment may be achieved by applying Steiner techniques to the minimal pipeline route calculation. However, suffice it to say that, at most, the shortest possible alternative to Palliser is 13.4% shorter than the MST, or 721 km. It is also important to note that the Palliser Pipeline designers were probably unaware of or disinterested in any techniques which could achieve this global minimum, and thus the MST length is probably the more appropriate measure.

7.7 **Summary**

It is likely that the application of environmental valuation techniques will only increase the need for industry to account for and minimize environmental impact. Even without rigorous, consistent valuation methods groups have overthrown development projects in many occasions.

Pipelines, especially gas pipelines, are good candidates in the transportation industry for application of such environmental valuation techniques. This is true because increasing the length of pipeline routes has an impact only on the cost of construction, and no real impact on travel time, unlike the case of other transportation systems.

This chapter not only provides an overview of established valuation techniques and their pitfalls, but also presents a new technique for revealing an upper bound on environmental value in development projects, specifically pipeline projects. This method was demonstrated using the Palliser Pipeline as an example, and is subject to the criticisms of the revealed preference technique in general, those being data-intensive analysis requirements and difficulty in dissecting results for specific environmental attribute valuation.

CHAPTER 8

CONCLUSIONS

So that's my story, Jack.
I never believed how long it would take to write it all down, or how many pages it would take . . . . I used three pencils right down to knuckle-stubs, and a whole tablet of paper.

Red in Stephen King's
"Rita Hayworth and Shawshank Redemption,"
in *Different Seasons*, 1983, Penguin Books: New York, p. 99.

8.1 Overview

This work applies established network analysis techniques to the pipeline network design problem in an effort to develop straight-forward, analytical design tools for the pipeline industry. Several network concepts and problems are presented in the literature review, including the market area problem, minimisation of network length, and using network medians and centres to locate central facilities or hubs. Each subsequent chapter highlights one of these problems as it specifically relates to pipelines. Industry data and case studies are used to exemplify the proposed network techniques. The second-last chapter broadens previous consideration of environment in the optimisation process by focusing exclusively on the environment. More specifically, monetary valuation of the environment is explored and a new valuation method presented. Specific and significant contributions in each of the above areas are discussed in detail in the following section.

8.2 Significant Findings

Perhaps the most significant finding of this work was one of the first, for the apparent shortage of published research in the field of spatial network optimisation for pipelines led to the decision to study and write about the fundamentals of this topic. This work, therefore, makes a significant contribution to the body of knowledge regarding pipeline spatial network design. It was also mentioned in the main body of this work that the field of electricity transmission may contain some work which could be of value to the pipeline problem, due to similarities between the two systems, and should be review for this purpose.

The first network problem studied involved the application of the market area model, developed and applied by both Newell (1973, 1980) and Erlenkotter (1989), to pipeline networks. This approach met with one significant issue: the appropriate selection of a configuration factor, or k-factor, describing a pipeline transport distance metric. The common Euclidean and Manhattan distance metrics were not appropriate for pipeline network transport, which was shown to be more efficient than even the Euclidean, as-the-crow-flies, metric because nodes in a pipeline network may share pipeline sections between them, thereby reducing the transport distance per node. An appropriate k-factor for pipelines in Alberta was investigated by calculating the factor revealed by five pipeline systems in the province. The factor was shown to be in the range of 0.1 to 0.3. The average, k = 0.2, was used to calculate the "optimal" market area for sweet and sour gas plants in Alberta, and resulted in optimal plant sizes of $V^*_{sweet} = 2.4 \times 10^7$ m^3/d (850 mmcf/d) and $V^*_{sour} = 9.9 \times 10^7$ m^3/d (3500 mmcf/d). This result clearly dictates that only one central facility should be considered for all but the grandest of natural gas fields. Both V^*_{sweet} and V^*_{sour} are much larger than the average Alberta gas plant size of 9.9×10^5 m^3/d (35 mmcf/d) (Wearmouth, 1994).

Pipeline network designers in industry tend to rely on trial-and-error methods (Bolkan, 1991), rather than optimisation techniques, analytical or computational in nature, to plan pipeline developments. The second network problem examined resulted in a significant outcome with the development of an easy-to-use analytical algorithm for connecting pipeline nodes in a near-optimal configuration. This algorithm combines the simplicity of the minimal spanning tree (MST) with Steiner network principles to develop near-optimal network solutions. The existence of external influences, such as environment, existing corridors, and production considerations, make the exact spatial optimum inappropriate in almost every case, so that near-optimal alternative solutions provide equal value to the design process. A simple MST solution to a case study of the Amoco East Crossfield gathering system shows a 26% reduction in total network length.

The third problem studied was the problem of locating central facilities in pipeline networks. Central facilities in pipeline networks, such as gas plants, are analogous to switching centres in communications networks, with a few differences. The literature indicates the network median provides the optimal location for such facilities, and this site may be found using a simple distance-table solution method illustrated in Chapter 6. The process allows for the inclusion of different downstream transportation systems when determining the optimal facility location. Application of the technique to the Amoco East Crossfield system provides some insight into the factors which probably affected the gas plant location choice, and shows the actual location to be very near optimal.

The final significant development for pipeline designers is a method of revealing monetary values placed on the environment by pipeline builders. Comparison of actual, as-built, pipeline structures against near-optimal spatial solutions, configured using the techniques presented herein, should always result in some difference. This difference will exist for a number of reasons, many of which are unknown to the researcher looking back at previous projects. At least one reason for building a longer-than-optimal pipeline is to avoid certain environmentally sensitive areas, rugged terrain conditions, or to take advantage of existing corridors, natural or man-made. By relating the differential construction cost of the non-optimal, actual design to the value of the avoided environmental costs, an upper bound on the revealed environmental value is obtained.

While it may seem somewhat insignificant to calculate only an upper bound on environmental value, and not an exact value, it is nonetheless an insight to a problem which has received little attention in pipeline circles. In fact, some established valuation methods, such as the Travel Cost Method, reveal only a lower bound to the same problem, so that this method may be at least as valuable as some others.

8.3 Strengths and Weaknesses

The greatest strength of this work is the set of practical tools developed specifically for pipeline network designers, all based on the fundamental principles of network optimisation. The analytical approach to pipeline design problems relays an almost immediate insight into the heart of the pipeline problem that is not often a clear result of computational solution methods.

Additionally, the cross-over of traditional petroleum engineering problems with transportation engineering methods has uncovered a fresh perspective on what many would consider an old problem, giving rise to creative, new solutions. Even the characterisation of pipeline networks presented early in the work, including such descriptors as commodity, insignificant transport time, and mode-captive, were surprising to industry experts and transportation engineers, alike.

A number of separate, but related, pipeline issues are dissected, including central facility density, spatial network design, facility location and specific environmental design concerns. While the methods presented will certainly not solve every problem associated with pipeline network design, a logical method is illustrated and may be expanded by including additional steps which were not considered.

Although the pipeline industry currently spends much time and energy on environmental issues, including environmental impact assessments, reducing plant and compression emissions, and the prevention of line ruptures, the concept of environmental valuation has received little attention from petroleum engineers. The author, however, was quick to perceive a much higher level of interest in the valuation techniques discussed in this work, than in the network techniques, at an industry conference at which presentations were made on each of the two subjects. The environment is receiving increasingly high levels of interest from the public, regulators, and industry, and may not be ignored. Techniques such as environmental valuation may provide an essential tool for the future development of pipelines, when public awareness and concern for our natural environment further increases to levels at which projects are increasingly rejected in favour of environmental preservation.

It is also important to highlight some of the short-comings of this work for the benefit of future researchers. A point mentioned earlier in this chapter drew a connection between the pipeline network and an electricity transmission network. The similarities between the two are in part a result of the fact that both move energy along a linear transmission system by virtue of flows. Unfortunately, the published literature in the field of electricity transmission was not reviewed in any detail for network research which might have related, by virtue of system similarities, to pipelines. Future researchers are advised to consider this related knowledge base.

Greater input from industry engineers might have done much to ground the insights and network methods presented here in practical problems. Illustrative case studies put the proposed methods to real data, but obvious applications to related or alternative problems, and similarly obvious pitfalls of the methods presented could have been more thoroughly examined by practitioners. While a somewhat academic approach to the pipeline network problem can sometimes offer the distanced perspective necessary to shed new light on a problem, it may also benefit from the wisdom of experience. The author suggests that researchers in all disciplines, but particularly this one, encourage critical examination of ideas amongst academic and industry experts alike. In fact, industry reaction to the ideas presented herein may provide a take-off point for future research in the area.

8.4 Future Research

The ideas presented in this thesis are intended to be the basis for future work in pipeline networks, and the author encourages the critical examination of this work for the purpose of expanding the body of knowledge and workable solution techniques in the field.

Most of the techniques presented herein receive only preliminary testing using real data. For instance, the application of the market area model could benefit from refining each of the gas plant cost function, the appropriate network k-factor, and other calculation parameters such as unit transport cost, γ, and production density, ρ. By testing the techniques more rigorously, relationships will certainly emerge that were not discussed in this work. This is almost always the case as one looks more closely at a problem which was thought to be solved, only to discover a more complex relationship at work.

The spatially optimal network is said to provide the designer with a starting point from which derivations will certainly be necessary in real problems. Environmentally sensitive areas in the network region are stated as one obvious external consideration. There are many other non-spatial considerations which are not dealt with in this work, and which can occupy the bulk of a pipeline engineer's energy. Some of these would include pipeline pressures, a direct result of well-head pressures, line compression and terrain topology, sub-central processing for water knock-out, and line heating, to name a few. A review of these external decision factors and their influence on the design elements discussed in this work would expand the applicability of pipeline network research for industry professionals. Knowledge of these influences would also enable computer modelling of the design process at a very realistic level.

Certainly, the transformation of the analytical techniques presented into computational tools for desk-top availability could increase access to network optimisation theories, while enabling engineers to include non-spatial design elements in the process. Further research on the topic of these non-spatial elements and their logical influences could inject some artificial intelligence into a computerised design model.

Lastly, the simplifying assumptions underlying the analytical models used in this work do not provide clear direction to the engineer with non-ideal design parameters. For instance, the assumption of uniform production density in the application of the market area model gives no direction regarding non-uniform production profiles. The application of the basic principles suggested here need to be tempered with an understanding of the impact of real, sometimes complex, problem attributes.

8.5 Summary

Starting from a fairly uncluttered research space on the topic of spatial network optimisation for pipelines, this work characterises the basic pipeline network and proposes a number of analytical solution methods for obtaining near-optimal networks. The research brings together a common petroleum industry problem with standard transportation engineering solution methods, to create a non-traditional approach to pipeline network design. It is hoped that the techniques developed herein will be applied and expanded by industry practitioners and academic researchers to achieve greater efficiencies and economies, to the benefit of producers, shippers and consumers of natural gas.

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APPENDIX A

The HaMSTer Program

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APPENDIX A

THE haMSTer PROGRAM

A.1 Introduction

This appendix introduces and explains the principles behind the program haMSTer. The program helps the user determine the construction and total link length of the minimum spanning tree (MST) for a set of points. The program is written in spreadsheet form using *MS Excel v. 5. 0c*. An overview of the logic used, distance calculations performed for systems on the surface of the earth, required inputs and general operation is presented in the following subsections.

A.2 The haMSTer Algorithm

A minimum spanning tree may be constructed using the following simple algorithm:

1. Select any node, n, from the set of nodes, N, to be connected in the MST,
2. Call the node(s) which have been selected [n] and those which have not yet been selected [n'],
3. Create a link between the two closest nodes, one of which is in set [n] and one of which is in set [n'], and move the node previously in [n'] into [n],
4. If any nodes remain in set [n'] go back to step (3).

These principles were followed to create a spreadsheet program that assists in generating a MST from a set of unconnected nodes.

The required inputs to the program are only the number and locations of the nodes, using either plane orthogonal Cartesian co-ordinates or degrees of latitude and longitude. The program calculates the distances between every pair of nodes and displays these in a distance table. The distances are sorted in ascending order and displayed alongside the two nodes for which the distance is calculated. At this point the user becomes interactively involved in creating the MST.

The principles of selecting links to create a MST are basically that, beginning arbitrarily, always select the next link between the closest two nodes, one of which is already connected and one of which is not. The program indicates to the user those links which are ineligible for selection due to the fact that both nodes are already connected. The user only needs to keep track of which nodes are in the connected set [n], and search the list for the shortest (highest in the sort order) distance which is eligible and which contains one node which has been previously chosen. When this link is found, the user selects it by typing "YES" in the column titled "Pick It" and records the order of link selection in a column titled "Order". The program automatically updates the eligibility column and the next link may be selected.

haMSTer is designed for a maximum of thirty nodes, but is easily expandable for up to fifty nodes. *MS Excel* could handle over 100 nodes, but the calculation time becomes unreasonably long after fifty nodes. Using a 486 DX 66 MegaHertz computer with 16 MegaBytes of RAM, a 22-node tree was constructed in fifteen minutes.

A.3 **Inter-Nodal Distance Calculations**

MST is capable of calculating either Euclidean distances or arc-length distances over the surface of the earth. The two accepted location systems are plane orthogonal Cartesian co-ordinates and degrees of latitude and longitude. The Euclidean distance between two points, *i* and *j*, is calculated using the familiar equation:

$$d_{ij} = [\ (x_i - x_j)^2 + (y_i - y_j)^2\ ]^{1/2} \qquad \text{(A.1)}$$

where:

d_{ij} = Euclidean distance between points *i* and *j*,
x_i = x-coordinate for the location of point *i*, and
y_i = y-coordinate for the location of point *i*.

The global co-ordinates measured in degrees of latitude and longitude can be used to determine the distance between points along the curved surface of the earth. Using the simplifying assumption that the earth is a perfect sphere, appropriate for the short global distances of concern in this work, the distance between two points may be determined using the following two equations from Maling:[1]

$$s_{ij} = R \cdot z_{ij}, \text{ and} \tag{A.2}$$

$$\cos(z_{ij}) = \sin(\varphi_i)\sin(\varphi_j) + \cos(\varphi_i)\cos(\varphi_j)\cos\delta\lambda, \tag{A.3}$$

where:

s_{ij} = arc length on surface of earth between points *i* and *j*,
R = radius of the earth, taken as 6371.2 km,
z_{ij} = angle between points *i* and *j* measured at the centre of the earth,
φ_i = degrees of latitude at the location of point *i*, and
$\delta\lambda$ = difference in degrees of longitude between two points, *i* and *j*.

It follows from Eqns. (A.2) and (A.3) that

$$s_{ij} = 6371.2 \text{ km} \cdot \text{Acos}\,[\sin(\varphi_i)\sin(\varphi_j) + \cos(\varphi_i)\cos(\varphi_j)\cos\delta\lambda]. \tag{A.4}$$

Equations (A.1) and (A.4) are used in haMSTer to determine inter-nodal distances in their appropriate contexts. haMSTer provides output displaying the tree structure in tabular form, much like a distance table indicating where links exist, and in graphical form. The total tree length is also calculated.

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[1] Maling, D. H. 1992. *Coordinate Systems and Map Projections*, 2nd Ed. Oxford: Pergamon Press.

APPENDIX B

The BISECTOR program

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APPENDIX B

THE BISECTOR PROGRAM

B.1 Introduction

The BISECTOR program was designed for the simple purpose of locating the point along an arc on the surface of the earth which is closest to another point off the arc on the surface of the earth. This calculation was necessary for locating T-junctions in pipeline networks to shorten a minimal spanning tree (MST).

B.2 Mid-link Connections for Shorter Networks

A MST network contains links which begin and end at the network nodes. Figures B.1(a) and B.1(b) illustrate that overall link length can be shortened by relaxing this requirement to allow mid-link connections, as is routinely done in the pipeline industry.

(a) MST Network

(b) Network with one mid-link connection

Figure B.1: Comparison of link construction techniques

A program has been developed which calculates the locations of points such as F in Fig. B.1(b) using global coordinate systems appropriate for structures built on the surface of the earth.

B.3 Spherical Trigonometry

A branch of mathematics called spherical trigonometry can be used to determine perpendicular bisection locations, on the assumption that the earth is a sphere. A step-by-step procedure for determining the co-ordinates of the new pipeline connection location follows. The formulas presented are taken from Maling[2] and Mackie[3].

A simple network composed of three points illustrates the required approach for solving the co-ordinates of the point which creates a T-junction between the three points. Figure B.2 shows three such points on the surface of the earth.

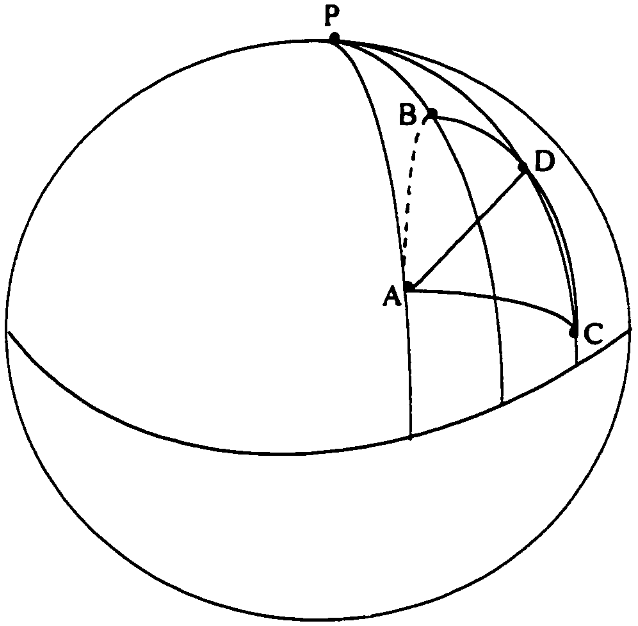

Figure B.2: A network of points on the surface of the earth

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[2] Maling, D. H. 1992. *Coordinate Systems and Map Projections*, 2nd Ed. Oxford: Pergamon Press.
[3] Mackie, J. B. 1985. *The Elements of Astronomy for Surveyors*, 9th Ed. High Wycombe, England: Griffin.

The MST for the points A, B and C includes the two links **AC** and **BC**. The degrees of latitude and longitude of A, B and C are known. It is desirous to know the location of the point D. The mathematical principles of the spherical triangle are presented here in order to solve this problem.

The spherical triangle PAC may be used to determine the angle ∠PAC from the known co-ordinates of the three points ($\varphi_p = 90^\circ$, $\lambda_p = 0^\circ$). If the co-ordinates of the three points are known, the length of each side of PAC may be determined using Eqn. B.1. It should be noted here that the length of a side of a spherical triangle is measured in degrees at the centre of the earth. If three sides of a triangle are known, an unknown angle, in this case ∠PAC, can be solved using

$$\cos A = [\cos a - \cos p \cdot \cos c] / [\sin p \cdot \sin c], \quad \text{(B.1)}$$

where:

A = angle at A,
p = side opposite point P,
c = side opposite point C, and
a = side opposite point A.

The length of side **BP** may be determined using the sine law for spherical triangles:

$$\sin A/\sin a = \sin B/\sin b = \sin C/\sin c \quad \text{(B.2)}$$

where terms A, B and C are angles in a triangle, and a, b and c are sides opposite these angles in the same triangle. Since the length of **AB**, the angle ∠BAC and the angle ∠ADB are known or may be determined using the above formulae, **BD** may be found using:

$$\sin\angle BAD/\sin \mathbf{BD} = \sin(90^\circ)/\sin \mathbf{AB}. \quad \text{(B.3)}$$

The length of **AD** may now be found using the simplified formula

$$\cos c = \cos a \cdot \cos b \quad \text{(B.4)}$$

for right-angled spherical triangles where c is the length of the hypotenuse. Applied to the triangle ABD, the formula is

$$\cos \mathbf{AB} = \cos \mathbf{AD} \cdot \cos \mathbf{BD} \tag{B.5}$$

which may be solved for **AD**.

The triangle PAD can now be used to determine the co-ordinates of the point D. Using the cosine formula it is possible to solve for the length of **PD**, as follows:

$$\cos \mathbf{PD} = \cos \mathbf{PA} \cdot \cos \mathbf{AD} + \sin \mathbf{PA} \cdot \sin \mathbf{AD} \cdot \cos\angle\mathbf{PAD}. \tag{B.6}$$

The complement of the latitude of a point is termed its Colatitude ($90^\circ - \varphi$). **PA** is the Colatitude of A and **PD** is the Colatitude of D. Hence, Eqn. B.6 yields the latitude of D.

The angle $\angle$APD may be defined as $\lambda_D - \lambda_A$. Thus, the longitude of D may be found from knowing $\angle$APD. This angle may be found using the sine law on triangle PAD.

The program BISECTOR, written in the spreadsheet software program *MS Excel v.5.0c*, uses the above procedures to determine the exact co-ordinates of points like D for a given set of three points in a network. The program requires only the degrees of latitude and longitude for each of the three points under consideration. It may not be clear which of the two links in the three-point, two-link mini-network should be shortened to achieve the greatest reduction in link length. For this reason, the program calculates the geometry of each of the two options and recommends the one which offers a shorter overall link length.

The program accepts up to ten sets of three points. If more sets of points need refinement the program must be run more than once. The results include the locations of the mid-link connections and the reduction in total link length achieved.

APPENDIX C

Gas Plant Cost and Capacity Data

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APPENDIX C

GAS PLANT COST AND CAPACITY DATA

C.1 Sweet Gas Plant Cost and Capacity Data

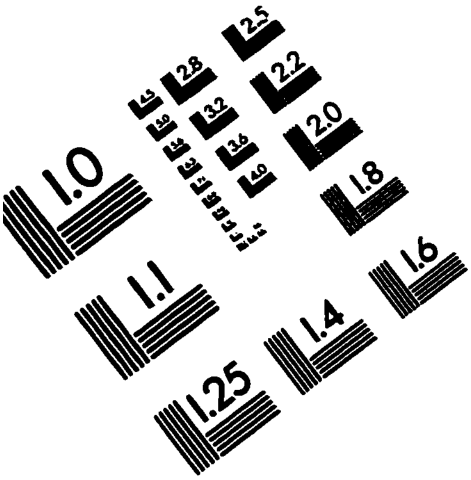
Plant Name	Location					Raw	Dry	Built	As-Built
	LSD	Sec	Twp	Rge	Mer	(000 m3/d)	(000 m3/d)		Cost ($000)
Ricinus	11	30	35	8	5	6229	5758	1973	28500
Elmworth	4	8	69	8	6	10028	9017	1979	43800
Bonnie Glen	SW	17	47	27	4	4226	3340	1975	29000
Dunvegan	NE	3	81	4	6	6762	6460	1973	21000
Elmworth	1	8	70	11	6	16200	15100	1979	30100
Pembina	13	24	48	7	5	3395	NGL	1958	11270
Wembley	6	19	73	8	6	3881	3508	1986	45000
Countess	12	33	22	18	4	1410	1380	1959	9950
Mitsue	NE	30	72	4	5	1700	1233	1970	13050
Nipisi	4	11	80	8	5	1840	1458	1984	32700
Karr	NW	10	65	2	6	3663	3347	1981	26600
Ricinus	6	31	33	7	5	2039	1999	1977	18000
Bigoray (Pembina)	10	7	51	9	5	895	704	1979	21180
Cranberry	1	24	96	5	6	2500	2256	1980	21900
Hamburg	NW	29	96	11	6	3800	3700	1986	31000
Marten Hills	12	18	76	25	4	4029	3944	1970	9200
Carson Creek	4	23	61	12	5	2450	2140	1962	7000
Leduc Woodbend	2	34	50	26	4	1632	789	1950	5000
Vulcan	8	24	15	22	4	1564	1226	1967	7000
Kaybob	8	9	64	19	5	5765	5267	1962	6000
Retlaw	12	19	12	18	4	1245	1045	1974	9000
Willesden Green	13	27	42	8	5	1126	1038	1981	17000
Peco	12	1	49	16	5	1982	1802	1980	14400
Ferrier	2	6	41	7	5	2817	2470	1970	6500
Swan Hills	3	18	67	10	5	1560	1466	1981	13000
Knopcik	9	10	74	11	6	2000	1880	1982	14800
Pembina	11	22	49	12	5	1220	1156	1981	11000
Carrot Creek	2	18	52	11	5	845	775	1981	11000
Wayne Rosedale	14	12	26	19	4	1714	1662	1981	10700
Niton	14	18	54	12	5	1784	1352	1977	7200
Wilson Creek	1	29	43	4	5	997	958	1967	3800
Pembina	9	17	50	7	5	1675	1600	1962	3275
Route	7	16	62	8	6	1981	1933	1982	12000
Whitecourt	12	26	59	11	5	1831	1730	1969	4000
Cessford	2	8	24	12	4	3522	3501	1958	2800
Brazeau River	9,16	35	48	12	5	1232	1126	1980	8000
McGregor	1	5	18	20	4	1043	873	1990	14000
Chinchaga N.	5	32	98	7	6	1339	1256	1983	10100
Ghost Pine	1,8	11	31	21	4	3099	2900	1967	3000
Sinclair	SW	19	72	11	6	1972	1955	1979	6500
Boundary Lake South	SE	14	85	13	6	1355	1332	1961	2490
Liege	12	31	94	18	4	1237	1189	1984	9500
Wapiti	16	36	67	9	6	8452	8343	1982	9000
Liege	6	29	92	20	4	1183	1133	1982	8000

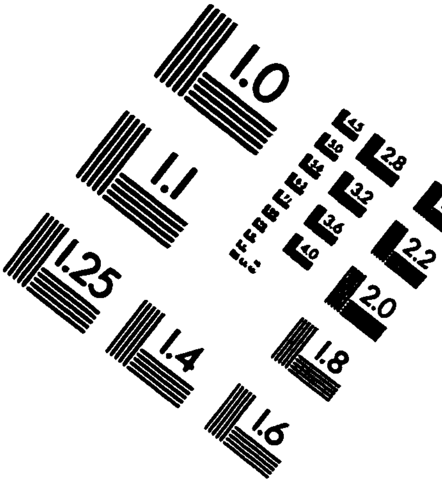
Plant Name	Location					Raw	Dry	Built	As-Built
	LSD	Sec	Twp	Rge	Mer	(000 m3/d)	(000 m3/d)		Cost ($000)
Bigstone	SE	10	61	22	5	900	840	1984	8000
Willesden Green	15	31	39	5	5	915	850	1985	8300
Worsley	7	22	87	7	6	1606	1465	1962	2000
Elmworth	4	8	69	8	6	3381	3366	1979	4900
Sylvan Lake	SE	21	38	2	5	811	733	1964	2000
Provost	8	19	36	5	4	2000	1409	1957	1770
Sylvan Lake	14	32	37	3	5	1837	1690	1965	2000
Josephine	NE	1	83	10	6	1409	1389	1978	5000
Liege	1	10	94	21	4	1005	977	1989	8500
Hussar	13	36	24	21	4	2367	2087	1959	1700
Hamburg	11	14	97	11	6	803	736	1992	9000
Nipisi	12	30	72	4	5	704	575	1975	3000
Gilby	15	22	30	3	5	2000	1700	1960	1600
Willesden Green	1	17	42	6	5	722	642	1965	1700
Prevo	5	1	39	1	5	850	782	1986	6500
Medicine River	5	5	40	3	5	1100	1004	1970	2000
Pouce Coupe	11	34	79	12	6	1155	1144	1986	6400
Niton	14	5	55	11	5	1250	1197	1987	6600
Nevis	NW	7	41	22	4	884	845	1982	5600
Big Bend	13	36	66	27	4	986	947	1977	3000
Connorsville	9	32	25	15	4	845	823	1977	3000
Pouce Coupe	3	3	81	13	6	1330	1314	1990	7000
Liege	15	30	90	19	4	722	700	1989	6000
Bolloque	16	2	65	25	4	708	705	1978	3200
Hussar	14,15	1	24	22	4	790	750	1983	3800
Bassano	10	5	22	18	4	704	700	1973	1500
Marten Hills	14	22	74	24	4	704	704	1969	1200
Leo	NW	24	36	17	4	710	685	1981	3000
Twining	4	33	31	23	4	1131	1092	1967	1000
Sunnynook	1	17	26	10	4	1133	1129	1988	3750
Cyn-Pem	7	7	51	11	5	887	837	1990	4100
Waskahigan	NE	7	64	23	5	1200	1160	1970	1000
Gilby	6	21	40	3	5	1475	1366	1970	1000
Ferrybank	2	1	44	28	4	732	694	1972	1000
Greencourt	9	26	59	9	5	1050	1016	1980	2000
Valhalla	1	29	75	9	6	1850	1820	1980	2000
Sylvan Lake	13	25	37	3	5	1090	1000	1974	1000
Parkland Northeast	7	11	15	27	4	846	835	1982	2200
Eyremore	1	18	17	18	4	700	684	1984	1600
Valhalla	8	20	76	9	6	1133	1097	1981	1300
Bruce	SW	6	47	15	4	845	845	1974	500
Stanmore	5	1	29	12	4	845	817	1973	350
Killam North	SW	5	45	12	4	704	703	1983	650
Hoole	10	24	81	25	4	917	906	1988	600
Countess	8	36	20	16	4	740	704	1960	110
Enchant	11	35	13	17	4	845	838	1960	37

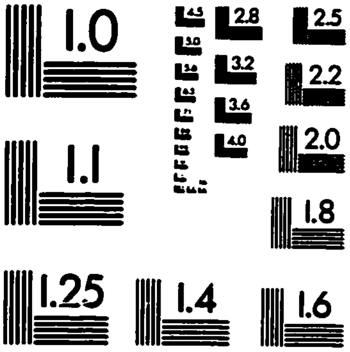
C.2 Sour Gas Plant Cost and Capacity Data

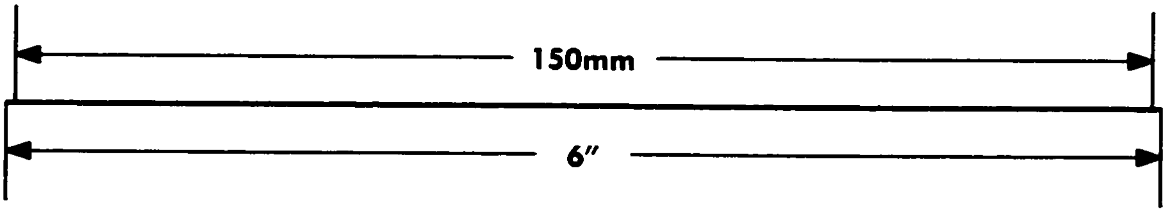
Plant Name	Location					Raw	Dry	Built	As-Built
	LSD	Sec	Twp	Rge	Mer	(000 m3/d)	(000 m3/d)		Cost ($000)
Caroline		34,35	34	6	5	9435	2630	1993	1000000
Jumping Pound		13,23,24	25	5	5	7686	5635	1951	152000
Waterton	17,20	10	4	30	4	13326	8875	1962	124500
Strachan	S	1,2	37	10	5	17749	12016	1972	120300
Kaybob South		11,14,15,22	59	18	5	19003	15145	1971	105800
Banshee		2,11,12	49	20	5	8610	6910	1982	250000
Harmatton Elkton		27,34	31	4	5	13900	12524	1960	66000
Bonnie Glen	SW	17	47	27	4	3097	1936	1954	49000
Kaybob South		1,12	62	20	5	11179	9062	1968	62000
Strachan	11	35	37	9	5	7748	5806	1971	61560
Crossfield		1,2	26	29	4	8988	6080	1961	40000
Nevis	NE	33	38	22	4	3653	3162	1956	34000
Crossfield East	9	14	28	1	5	5128	3212	1965	33500
Windfall	8	17	60	15	5	11941	4474	1961	31000
Burnt Timber	10	13	30	7	5	3610	3211	1970	31500
Rainbow	10	10	109	8	6	3800	2400	1968	27000
Carstairs	SW	3	30	2	5	9858	7888	1960	21000
Homeglen Rimbey	S	5	44	1	5	11918	9974	1961	20500
Quirk Creek	S	4	21	4	5	2536	1928	1971	19500
Sinclair	14	18	74	12	6	4970	4777	1981	45000
Rosevear	NE	11	54	15	5	1700	1430	1979	31000
Brazeau River		1,12	46	14	5	6180	5550	1969	14000
Minnehik Buck Lake	10	5	46	6	5	3635	3284	1961	11000
Edson	4	11	53	18	5	10548	9571	1965	11000
Paddle River	13	6	57	8	5	2440	2065	1966	10500
Lone Pine Creek	6	23	30	28	4	2096	1662	1966	9500
Progress	SE	1	78	10	6	3954	3850	1985	33000
Coleman	1	11	8	5	5	2113	1546	1962	8110
Caroline	1	11	35	6	5	2105	1865	1981	25000
Okotoks	SW	27	20	29	4	981	479	1959	6560
Simonette	9	6	63	25	5	1042	761	1969	8000
Wimborne	4	12	34	26	4	986	733	1964	6500
Zama	NW	12	116	6	6	1050	914	1976	11000
Caroline	3,4	20	34	4	5	1513	1070	1968	6500
Gold Creek	NW	26	67	5	6	1590	1420	1970	7000
Wildcat Hills	6	16	26	5	5	3522	2814	1961	5200
Rosevear	NE	33	54	15	5	1042	704	1976	10200
Lone Pine Creek	5	27	29	28	4	986	733	1971	6800
Brazeau River	4	31	48	12	5	3765	1927	1980	13100
Teepee	7	2	74	4	6	870	824	1977	7300
Brazeau River	W	10	44	12	5	1879	1690	1970	3000
Progress	7	22	78	9	6	1239	1184	1990	10000
Bigstone	SE	10	61	22	5	1578	1211	1968	2000

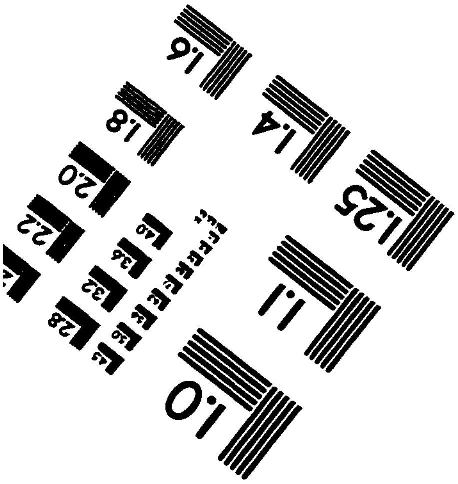
IMAGE EVALUATION
TEST TARGET (QA-3)











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