AN OPTIMAL DETERMINATION OF
LONGWALL PANEL DIMENSIONS

by

Okechukwu Onyebuchi Onyemaobi

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Approved

E. Topuz, Chairman

W. E. Foreman

J. Richard Lucas, Department Head

C. T. Shaw

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CHAPTER I

INTRODUCTION

As the U.S.A. continues to import an ever increasing portion of its energy sources, the task of developing domestic energy resources becomes more critical. Besides coal all other alternative energy resources such as oil and gas, nuclear, solar and geothermal suffer in varying degrees, either from their scarcity, or from technological and economical difficulties encountered in their production and utilization processes.

The development of domestic coal resources offers a readily available medium run solution to the energy problem. This development, however, also has some problems. Questions have been asked about the impact of coal production on air, water and land as well as on the health and safety of mine workers. There is considerable uncertainty about the consequences of environmental legislation and about the constraints and restrictions imposed on the industry. Despite these obstacles, the domestic coal production reached on all time high of 685 million tons in 1977. The National Energy Program projects a need of more than 1.2 billion tons in 1985. Various projections of the future energy requirements have estimated that the demand for coal as two to three billion tons a year or more by the end of the century.

After a quarter of a century of stagnation, the coal industry is expected to experience substantial growth. The domestic coal resources which are estimated by the United States Geological Survey...
as 438 billion tons of technically and economically mineable reserves, are sufficient to meet the increasing demand for more than 100 years.

The projected increase in use of coal requires development of new mines and expansion of the existing mines. The future challenge is not only to increase coal production but also to increase coal recovery and productivity as well as to improve the health and safety conditions and to minimize environmental disturbances resulting from the production processes.

In recent years, the gradually decreasing productivity of the workers in the domestic coal mining has made the longwall mining method an attractive choice to the industry. Although the initial investment for a longwall mining panel is substantially higher than that for room and pillar units, longwall mining offers potential for improved safety and productivity, better ground control, higher levels of recovery and lower unit production cost. (2, 3)

The production capacity of a longwall mining panel is determined by several factors, such as the rate of advance, the thickness of extraction, the working speed of cutting and transporting equipment, the width and length of the panels, etc. Some of these factors (external factors) are dictated by the environment in which the extraction process is to be carried out. These external factors include the geologic, tectonic and rock mechanics properties of the mine environment as well as thickness, depth, physical and chemical characteristics of the coal seams. Another group of factors (internal factors) can be manipulated by the decision maker (to a certain degree) in order to optimize the production of a system.
These factors include size and specifications of the equipment to be used in extraction, and the dimensions of the openings.

The width and length of a longwall panel together with the rate of face advance are the most important internal factors which determine the output of a panel. These critical factors are commonly determined by rule of thumb rather than by serious investigations. This thesis investigates the effect of the width and the length of a longwall panel on its production capacity and suggests a methodology for an optimal determination of these factors.

In Chapter II, a historical review of longwall mining applications and its different configurations are presented.

Chapter III states the problem to be solved and reviews the literature relevant to the problem.

Chapter IV draws the boundaries of the problem, analyzes the problem, identifies the variables involved, states the relationships among the variables and provides a general formulation for the problem.

In Chapter V an application is made to a hypothetical coal seam using the four different objectives to solve for the optimum dimension of a longwall mining face.

Chapter VI draws conclusions and makes recommendations for future studies.
CHAPTER II
LONGWALL MINING SYSTEM

2.1 History of Longwall

The longwall mining system was probably first used in the early 18th century in Shropshire, England. At that time it was named the "circular" method because of the plan view of the operations. This was the method of coal mining for many years. The method was advancing with entries to the face radiating out from a central shaft. Advance entries were kept open by using packwalls, cribs, and timbers. The faces were also supported by the same material. (1, 4)

At first coal was used in Great Britain for space heating. When the demand for coal increased as a result of industrialization, this circular mining method became more organized. It changed from a one shift operation to a three shift operation. The first shift undercut, drilled and shot down the coal. Hand picking and loading were done in the second shift, while the third shift built packwalls, moved the haulage rails and prepared the face ready for the next operation.

These early operations were primitive, inefficient, and labor intensive even though some machines such as hand operated coal cutters were used to undercut the coal seam. The development of compressed air (1850) and electricity (1890) as power sources for underground mining operations were major improvements leading towards the progressive mechanization of the coal face. (5)

Longwall mining was introduced into the Midwestern coal fields of the United States in the early 1800's, and used in coal beds of
shallow depth. Most of them were closed in the 1920's though there was still one "circular" operation in 1961 at Centerville, Iowa. (6, 7, 8)

Until the 1930's timber was used for roof support. Wooden props did not last long as support material, as they proved cumbersome and time consuming to install. Although coal cutting technology had been improved, the longwall method could not significantly increase coal production until better face and roof supports were developed. (5, 9)

Before World War II, some mechanization was introduced into longwall faces in Great Britain and Germany. As a result of the war further improvements were made in longwall mining. The British developed the shearer and the shearer trepanner, which is similar to the shearer except that it rotates in the vertical plane, and the Germans originated the plow. The British introduced the hydraulic, self-propelled roof support jack in 1947. The introduction by the Germans of the flexible armored conveyor before the war helped revolutionize the longwall mining system. After the war, the German mining engineers came out with a new longwall conveyor to work with their system of coal ploughing. This was a high recovery method for their soft coal seams and this new conveyor was officially called "Armored Face Conveyor" or AFC. (10, 11)

By the early 1950's the double unit longwall, with two belt conveyors loading into a central mothergate was well established. The coal was undercut some five or six feet, drilled and blasted ready for loading. Hand set mechanical and hydraulic supported props and bars
supported the roof of the working area while strip packs were used for roof control in the gob area. With time, the wooden props were replaced by hydraulic telescopic props. These props were equipped with release valves to change their lengths and they worked well on hand loaded faces. (12)

The first change in longwall from a cyclic to a continuous operation came as a result of the introduction of the armored face conveyor and power loading machine. The real breakthrough, however, occurred as a result of the development of powered roof supports which helped to reduce manpower, increased rate of advance, provided better roof control of the strata, and increased safety. (13, 14)

The first mechanized longwall panel in the U.S. was applied in the early 1950's in West Virginia. The German coal plough was used for soft coal, and for hard coal, the British Anderton Shearer was used. In 1951 a mine owned by Barnes and Tucker Company in Central Pennsylvania installed a Mover and Coulson Wedgehead Stripper and Conveyor. Roof support was provided by individual Dowty 20-ton hydraulic props. (6, 15, 16) Other countries such as Australia, South Africa, and India which traditionally had used the room and pillar methods started to install longwall faces with different degrees of mechanization. Most of the early mechanized faces were not very successful. Those early systems concentrated mainly on roof support. The roofs were supported by single either hydraulically or mechanically operated jacks supplemented with wooden cribbing. This type of support needed large crews to handle the heavy equipment as well as to build the cribs.
As a result of these improvements, longwall mining has quickly changed from an inefficient and cyclic operation to a highly efficient, mechanized, continuous one, working on a three shift basis. At present, in several countries the longwall mining accounts for a substantial part of underground coal production. In Great Britain longwall method is used in most of the coal mines, making that country the second in coal production using longwall mining. Production from longwall faces in Great Britain accounts for 92 percent of total underground coal. The U.S.S.R. is the leading world producer from longwall mining faces. (11, 12)

In the U.S., the longwall mining system has been slow in acceptance because of the prevailing geologic conditions of the coal seams. The relatively thicker horizontal, and shallower coal seams make it more economical to mine by the room and pillar method. In 1975 longwall mining accounted for less than four percent of total underground production, though this figure is expected to rise to about fifteen percent before 1985. The U.S. Bureau of Mines recently published a report that there are about seventy-two faces in operation, while five years ago there were only forty faces. (17) In the next three years it is projected that there will be about 140 faces installed, an unusually rapid increase in the use of the longwall. Most mine operators have now realized the potential of longwall mining in terms of safety, efficiency, mass production, and better ground control.
2.2 The Longwall Mining System

In longwall mining, coal is produced from a face or wall that is blocked out between two sets of butt or panel entries. The length of the coal seam is traversed by huge cutting heads called shearsers or plows. This equipment cuts the coal and dumps it onto a conveyor which hauls it to the end of the panel.

The miners work under a protective canopy of steel supported by jacks or props. As the shearer or plow completes a pass, the whole system, i.e., conveyor, canopy, shearer or plow is moved forward, and the strata behind the support are allowed to cave. (18, 19, 20)

There are two main types of longwall system used today: retreat and advance. In addition to these main configurations, various heading arrangements are being applied in many mines in Europe, such as, Z pattern, retreat between advance, or advance with two headings. (21, 22)

The choice of any method depends on the rock mechanics, past mining experience and the laws and regulations of the country. A brief description of the two main methods as well as their advantages and disadvantages is given below.

2.21 Retreat Longwall Mining

The retreat longwall mining method is generally employed in Europe, particularly in France, and West Germany, because of the geologic conditions of coal seams in these countries. This method is also relatively common in the U.S. because of the experience of the American mining engineers. One of the main requirements in application of this method is that the roadways must stand without
necessitating any major maintenance for the life of the face. The U.S. seams have been laid down in strong strata, making it possible for this requirement to be satisfied by the use of roof bolting.\(^{(23)}\) Also, since the depth of cover for most bituminous coal mines is shallow retreat longwalls are very successful.

In the retreat longwall mining method, the practice is to drive pairs of entries out to a boundary where they are joined by a face heading. Then using the face equipment mining is retreated to the starting position (See Figure 1). In the U.S.A., the law requires bleeder entries to carry noxious gases to the main return airways and to help ventilate the gob area. The longwall equipment is set across the face which extends from No. 2 butt or panel entry to No. 3. The shearer or plow cuts the coal and discharges it onto the face conveyor which is installed parallel and adjacent to the longwall face. The face conveyor is pushed forward by hydraulic rams as the coal is mined, and the roof support is advanced. The broken coal is discharged onto an entry conveyor which carries it to an extensible belt conveyor that moves the coal from the first belt into the mine car or main entry belt, which, in turn, carries it to the plant. When the panel is mined back to 'A' entry, the equipment is disassembled and moved into another panel.

The retreat mining system has many advantages over the other configurations of longwall mining in the U.S. The Federal Health and Safety Act of 1969 stipulates that intake air may not be passed over a cross belt and must be overcasted. Furthermore, air passing through development faces must not be used to ventilate a longwall,
Figure 1. Retreat Longwall Mining

SOURCE: Ref. 4, p. 12-75.
regardless of whether or not the mine is gassy. Additional entries would be required to get sufficient air for splitting and for neutral belt entries which compound the development problems as well as reduce the recovery of reserves. (24, 25, 26) Other advantages include reduction of encountering unknown geologic hazards, since headings around the area to be extracted have been driven prior to the face operations. The roadmaking processes are separated from the production operations which leads to simplification of the total design. Packs and ribs are also eliminated since there is no need to support roadways in the goaf area. The risk of spontaneous combustion is reduced. Finally, there is greater consistency in performance and faster rates of advance which leads to higher outputs and higher efficiency.

On the other hand, development must keep pace with retreat mining. It may take about ten months to develop a panel, while extraction of that panel may take only five months. Therefore, there is a significant length of time between starting development work and commencing production in any panel; which constitutes a major disadvantage to the system.

2.22 Advance Longwall Mining

The advance longwall mining is extensively used in the United Kingdom. It provides flexibility in a wide range of geologic conditions. It has not been easy for British mining engineers to change from this method to the retreat system because of the belief that any change will be expensive and will likely
depress results beyond acceptable limits. The British also fear that as retreat longwall mining needs prior development work, a change to it will necessitate more development equipment.\(^{(27,28)}\)

In the advance longwall mining, the coal is extracted away from the main entries (Figure 2). Packs are built on roadside or substitutes are necessary for ground support in roadways and ventilation opening. The stable is a short space excavated at the face end in advance of the face line, and provides room for the face conveyor drive. It also provides an opening for the face loader to pass at the end of the run. It can also be used for turning the face cutting machine–drum.

The advantages of the advance longwall method include early production from a face without waiting for the entire panel to be developed. It is also suitable in multi-seam mining and where there is insufficient knowledge of strata behavior and control.

On the other hand, the disadvantages include forming and operating the face end, and making sizable roadways as fast as coal can be taken off the longwall. There is difficulty in bringing supplies into the face and also in controlling gas emission. It is costly to recover the equipment and at times it is lost.\(^{(29,30)}\)
Figure 2. Advance Longwall Mining

SOURCE: Ref. 30, p. 104.
CHAPTER III

STATEMENT OF THE PROBLEM AND REVIEW
OF RELEVANT LITERATURE

3.1 Statement of the Problem

The question that is often asked is what should be the dimensions of the longwall panel in order to optimize the rate of face output? The dimensions of a longwall panel are critical parameters too often determined by rule of thumb rather than by serious investigations.

The objective of this thesis is to determine the optimum dimensions of a longwall coal mining face. This thesis is an economic study and no consideration has been given to technical limitations resulting from rock mechanics problems and the geology of the area.

3.2 Review of Relevant Literature

There is a shortage of published information regarding the optimum dimensions of a longwall face. The few articles reviewed in the following pages mostly came from European countries.

Muysken and Tillessen\(^{(32, 33, 34)}\) investigated the optimum face lengths in 1966. They derived the following equation:

\[
K = d + \frac{a}{L^V} + \frac{C}{V} + \frac{b}{L}
\]

Where \(K\) represents the costs for each square meter of surface working, \(L\) is the length of longwall face in meters, \(V\) is the daily face advance in meters, \(d\) is the costs for moving of face support for per square meter of surface working, waste and repair, and cost of construction
per square meter, \( a \) is the material costs at the head and the foot of the longwall face and power costs, \( c \) is cost of rentals or claims for face support per meter length of longwall face per day, and \( b \) is the proportional costs of the rate of face advance for per meter, which includes the working costs at the crossing of the longwall face and gallery, the working and material costs for tunneling and maintenance and withdrawal of the galleries in the seam.

Muysken and Tillessen stated independently that in general, the high investment for face equipment favors the installation of short faces with high daily advance rates. However, this may be offset by the development, installation, and withdrawal costs which grow steeply with decrease in face lengths. They concluded that the optimum face length is between 200 and 250 meters.

Peter (35) in 1966 stated that the economic length for R.O.L.F. (Remote Operated Longwall Faces) equipment lies within the range of 125-220 yards for a thirty-nine inch coal seam. He found that for a single face operation the cost per ton of coal mined gets higher as the face length increases.

Trevorrow (36) in 1968 reported that face lengths vary from 400 to 510 feet, while panel lengths range from 1500 to 4500 feet. The trend at Barnes mine in 1968 was toward wider and longer panels to reduce the development work and extend the time interval between each moving and installation operation.

Holland and Cakir (37) in 1968 stated that longwall faces should be in the range of 600 to 900 feet, and that the most economical face length may be between 400 and 500 feet.
Ford (38) in 1970 formulated the expression for the cost per ton of a longwall face as:

\[
\frac{1}{.9HFA} \times \left( \frac{c + w + fA + CDF}{S} + W \right) + X + R
\]

Where \( H \) is the seam height in yards, \( F \) is the face length in yards, \( A \) is the face advance per shift, \( c \) is the capital cost to equip two roadways (for drivage), \( d \) is capital charges and maintenance rate per annum for roadway equipment, \( S \) is number of shifts worked per annum, \( w \) is wages cost for two roadways per working shift of the face, \( f \) is fixed roadway cost per yard for two roadways, \( A \) is face advance per shift, \( C \) is capital cost to equip the face, per yard, \( D \) is capital charges and maintenance rate per annum for face equipment, \( W \) is wages cost in face per shift, \( X \) is overhead costs per ton, and \( R \) is equipment installation and withdrawal costs per ton.

However, Ford did not use the above equation in his approach. His solution was the same approach others had used before him, that is assigning numbers for annual depreciation, production, operating costs and calculating the cost per ton from them. He concluded that the length of a mechanized face has an important influence on the economics of coal production. The face lengths which produce optimum results depend on seam height, rate of output, and the size and type of the gate roads used. He recommended that face lengths should be in the range of 150 yards, and that face lengths are best determined by practical rather than economic considerations such as the horsepower required for the face.
finally, Aman in 1975\(^{39}\) in a study for his company came out with a preliminary result for a non-coal mineral that the optimum face length may be approximately 1000 feet using a panel length of 2500 feet. His recommendations also state that a longer face length may be prohibitive due to excessive equipment requirements.

In summary, the above studies and papers suggest that the optimum length of a longwall unit lies in the range of 300 to 1000 feet. This study differs from the ones aforementioned in that it is a mathematical approach that identifies the variables in a longwall system and establishes the relationship between the variables, and provides solutions under different objectives.
CHAPTER IV

FORMULATION OF THE PROBLEM

This chapter presents the objectives and assumptions used in the formulation of the problem, identifies the variables involved, defines the relationship between the variables, and provides mathematical formulations of the problem for various objectives.

4.1 Objective Criteria

The formulation of the problem has been attempted under four different objectives considering the fact that each of these objectives may capture a partial interest of the decision maker. These objectives are given below:

(1) Minimize average unit production cost.
(2) Maximize the internal rate of return of annual cash flows.
(3) Maximize the profitability index.¹
(4) Minimize the present value of the average unit production cost.

4.2 Assumptions

In the formulation of the problem the following assumptions are made:

¹Profitability Index is defined as a ratio of the net present value of cash flows to the initial investment.
(1) The decision to apply longwall mining as a method for the recovery of coal is given by management. Therefore, other possible mining methods are not considered.

(2) This study is an economic one, therefore the effects of possible limitations that may be imposed by rock mechanics, geology, and other external factors are not considered.

(3) Necessary additional capital funds are available at the same cost of capital as the initial capital.

(4) Costs of development and transportation up to the entry of the longwall panel are disregarded. Because these development, transportation, and service costs would be incurred regardless of the panel length and of other alternative methods used in production process.

(5) The relationship between panel dimensions and some cost items are assumed to be

   (i) Linear such as shield, belt conveyor and armored conveyor, or

   (ii) Nonlinear such as stage conveyor, conveyor belt drive units etc., (in such a case the "Sixth-Tenths Factor" was applied), \(^1\) or

   (iii) Fixed cost items, such as shearer or plow.

(6) During development continuous miners are used to open headings and breakthroughs. The unit cost of this operation is

---

\(^1\) The "Sixth-Tenths Factor," an empirical formulation indicates that if \(I'\) is the necessary investment for the plant size \(C'\), then, the estimated investment \(I''\) for a larger plant size \(C''\) is given by: \(I'' = I'*(C''/C')^{0.6}\).
assumed to be partly constant and partly varying with panel length to account for transportation. For the constant portion, a fixed cost per ton of production is assumed for all face lengths.

(7) If face length varies within certain limits, the manpower requirements for a longwall face are assumed fixed. If the face length varies beyond these limits manpower requirements need to be revised.

(8) No consideration is given to the opportunity cost of the level of recovery which varies with length of a longwall face. However, if the opportunity cost is known it can easily be added to the model.

(9) Finally, there are some other less general assumptions that are given under their respective headings.

4.3 Identification of Variables and Definition of Relationship Among Variables

The objectives stated in the previous section require calculation of the production, relevant costs, and cash flows obtained from a longwall panel depending upon varying dimensions of the panel. Therefore, the variables associated with a longwall panel may be classified into three general categories: production, costs, and cash flows.

4.3.1 Production

Production of a longwall panel can further be subdivided into two categories: development production, and panel production.
4.311 Development Production

The production from development comes from the headings, breakthroughs, and the preparation of the longwall face. There is no allowance given for pillar recovery.

The factors that affect the coal produced from development works are the number of headings, distance between breakthroughs and their cross sections, number of entries, length of the panel, density of coal and length of the face. Figure 3 shows the development work for a 3-heading entry. During the development of a panel the coal production from the headings and breakthroughs can be expressed as follows:

\[
\begin{align*}
Ph &= Y \cdot N \cdot W_1 \cdot H \cdot D \\
\text{and} \\
Pb &= \frac{Y}{W_2 + W_3} \cdot (N-1) \cdot W_5 \cdot W_3 \cdot H \cdot D
\end{align*}
\]

where

- \( Ph \) = production from headings,
- \( Pb \) = production from breakthroughs,
- \( Y \) = length of panel,
- \( N' \) = number of headings in an entry,
- \( H \) = seam height,
- \( D \) = density of coal,
- \( W_1 \) = width of a heading,
- \( W_2 \) = distance between breakthroughs,
- \( W_3 \) = width of a breakthrough, and
- \( W_5 \) = width of a pillar or distance between headings.
Figure 3. Development of Headings and Breakthroughs
Production from preparation of a longwall face can be expressed as

\[ Pf = W_4 \times X \times H \times D \]

where \( X \) is the length of a longwall face and \( W_4 \) is width of longwall face opening.

Total production from development (PD) is the sum of the production from the headings, breakthroughs and the face, or

\[ PD = Y \times N \times W_1 \times H \times D + \frac{Y}{W_3 + W_2} \times (N-1) \times W_5 \times W_3 \times H \times D + W_4 \times X \times H \times D \]

4.312 Panel Production

Panel production depends on several factors. These factors are analyzed and described as follows:

Shift Available Time

A normal 8-hour shift consists of 480 minutes. However, due to regulation, travel time, and scheduled breaks, the net time available for work—the face time—is substantially reduced. The average net time available before and after the 1969 act at most mines is 390 minutes. However, this time is further reduced by compliance with PL 91-173. In this study the average net time is taken as three hundred minutes.

Cycle Time

Cycle time here refers to the time necessary for the machine to complete one production cycle. This cycle time may be expressed by the following equation:

\[ T_{CYCLE} = \frac{X}{V_{mf}} + \frac{X}{V_{mb}} + L + a \times X \]
where:

\[ \text{TCYCLE} = \text{cycle time}, \]
\[ X = \text{face length}, \]
\[ \text{Vmf} = \text{velocity of the shearer machine in forward direction}, \]
\[ \text{Vmb} = \text{velocity of the shearer machine in backward direction}, \]
\[ L = \text{time required to make a change in direction and allowance for unscheduled delays and breakdowns, and} \]
\[ a = \text{maintenance and service time per feet of a face}. \]

**Production Per Cycle**

The production per cycle refers to the amount produced within one cycle time. Production per cycle depends on conveyor capacity, conveyor speed, travel direction of conveyor, depth of web, height of the coal seam, density of the coal, and length of face.

The production in a cycle in a unidirectional cut is given as:

\[
\text{PCYCLE} = d_1 \times H \times X \times D
\]

where:

\[ d_1 = \text{depth of cut}, \]
\[ H = \text{seam height}, \]
\[ D = \text{density of coal, and} \]
\[ X = \text{face length}. \]

The production in a cycle in a bidirectional cut is given as:

\[
\text{PCYCLE} = d_1 \times H \times X \times D + d_2 \times H \times X \times D
\]

The \( d_2 \) is depth of backward cut and the other terms have been previously defined.
The capacity of the conveyor is a function of its speed, and its cross section. Since the coal cut by the shearer needs to be transported by this conveyor there should be a balance between the rate of coal production and its transportation. This balancing relationship, following Teale (42) can be derived as follows:

\[ d_1 \cdot H \cdot V_{mf} \cdot D \cdot S \cdot \frac{S}{V_{mf} - V_c} \]

That is coal produced by the shearer on the left hand side is equal to the coal transported by the conveyor when both machine and conveyor are travelling in the same direction. Similarly the balancing relationship when both machine and conveyor are travelling in opposite directions can be expressed as:

\[ d_1 \cdot H \cdot V_{mf} \cdot D \leq S \cdot \frac{S}{V_{mf} + V_c} \]

Combining both equations into one we have

\[ d_1 \cdot H \cdot V_{mf} \cdot D \leq S \cdot \left| V_{mf} + K \cdot V_c \right| \]

or

\[ d_1 \leq \frac{S \cdot \left| V_{mf} + K \cdot V_c \right|}{V_{mf} \cdot H \cdot D} \]

where \( S \), and \( V_c \) are the capacity of the conveyor and its speed. \( K \) is +1 or -1 depending on the direction of travel.

Similarly for a bidirectional cut

\[ d_2 \leq \frac{S \cdot \left| V_{mb} - K \cdot V_c \right|}{V_{mb} \cdot H \cdot D} \]
Combining the equations 4.2 to 4.6 we can obtain the production per cycle in a unidirectional cut as

\[ \text{PCYCLE} = \frac{s \cdot \text{lvfm} + k \cdot Vc}{Vmf} \times x \] \hspace{1cm} 4.7

which is a function of face length, conveyor speed, conveyor capacity and machine speed.

Similarly, production for a bidirectional cut is given as:

\[ \frac{s \cdot \text{lvfm} + k \cdot Vc}{Vmf} \times x + \frac{s \cdot \text{lvmb} - k \cdot Vc}{Vmb} \times x \] \hspace{1cm} 4.8

**Production Per Shift**

The production in a shift can be expressed as a function of total available time in a shift, cycle time and production in a cycle.

\[ \text{PSHIFT} = \frac{\text{TA} \times \text{PCYCLE}}{\text{Tpc}} \] \hspace{1cm} 4.9

where:

- \( \text{PSHIFT} \) = production in a shift,
- \( \text{TA} \) = shift available time,
- \( \text{PCYCLE} \) = production per cycle, and
- \( \text{Tpc} \) = time per cycle.

**Production Per Year**

It is assumed that the longwall unit is operating three shifts per day and for 250 days in a year. Therefore, the total number of shifts in a year is 750. The total number of shifts in a year consists of shifts that are actually used for mining coal and shifts that are used for installation and withdrawal of longwall panels as the coal reserves
in a panel are exhausted. Consequently, the annual production is related to the amount of coal reserves in a panel, the number of shifts to mine coal from a panel and the number of shifts for installation and withdrawal of the machinery in a panel.

**Reserves in a Panel**

The amount of recoverable coal reserves in a longwall panel is a function of panel dimensions, seam thickness, density of coal, level of recovery and amount of pillars left to protect the openings. This functional relationship may be expressed as:

\[
Rp = X \times (Y - A) \times H \times D \times R
\]

where:

- \( Rp \) = recoverable coal reserves in a panel,
- \( X \) = face length,
- \( Y \) = longwall panel length,
- \( A \) = width of rib pillar,
- \( H \) = seam thickness,
- \( D \) = density of coal, and
- \( R \) = level of recovery.

**Shifts to Mine Coal From a Panel**

The number of shifts required to mine all the coal from a panel is given as:

\[
N_3 = \frac{Rp}{PSHIFT}
\]
where:

\[ N_3 \quad \text{number of shifts to mine coal from a panel,} \]
\[ Rp \quad \text{reserves in a panel, and} \]
\[ \text{PSHIFT} \quad \text{production per shift.} \]

**Installation and Withdrawal Shifts**

The face equipment should be moved from one face and installed in another face as the coal reserves in the former face are exhausted. The number of shifts required to move and install a longwall panel is assumed to be a linear function of the length of face.

\[ N_4 = M_1 \times X + M_2 \]

4.12

where:

\[ N_4 \quad \text{installation and withdrawal shifts,} \]
\[ M_1 \quad \text{a constant factor with face length,}^1 \text{ and} \]
\[ M_2 \quad \text{a constant removal and preparation time.}^1 \]

Consequently, the number of shifts required to produce all the coal from a panel and move the equipment to a new panel is the sum of the \( N_3 \) and \( N_4 \).

If \( N \) represents the number of panels to be mined in a year and 750 is the number of shifts available in a year, it follows that:

\[ N = \frac{750}{N_3 + N_4} \]

4.13

---

1 According to the present applications the value of the parameters \( M_1 \) and \( M_2 \) vary within the range of 0.05 to 0.2, and 0 to 20, respectively but in this study \( M_1 \) is assumed as 0.15, and \( M_2 \) as 10.
If we denote production from the longwall panel in a year as PAN, we can say that

\[ \text{PAN} = \text{Rp} \times N \]  

4.14

**Total Annual Production**

The total annual production (PT) is the sum of the total annual production from the development works and total annual production from the longwall panels.

\[ \text{PT} = \text{PAN} + \text{PD} \]

\[ = \text{Rp} \times N + \text{PD} \times N \]

\[ = (\text{Rp} + \text{PD}) \times N \]  

4.15

4.32 **Costs**

The costs of production from a longwall panel can be grouped into two categories: capital costs and operating costs. These two groups can further be subdivided into fixed and variable cost items in their respective groupings. The fixed cost items are assumed to be constant with a given range of production. Beyond this range, however, they are considered as variable items. The variable cost items, on the other hand, may vary directly (either linearly or nonlinearly) as the production varies. The following section classifies and analyzes the cost items which are directly related to the production from a longwall panel. Some other capital or operating cost items, such as reserve acquisition, engineering, services, all the development and operating costs from the portal of the mine to the entry of a longwall panel, etc. are not taken into consideration on the assumption that
these costs are not directly related to the dimensions of a longwall panel.

4.321 Capital Cost Items

The capital cost items which are directly related to the production from a longwall panel are the capital investments in the development works and the longwall panel.

Capital Cost of Development

In the U.S.A., the development is usually performed using continuous mining units. A continuous mining unit may include the following equipment:

(a) continuous miner,
(b) shuttle cars,
(c) loaders,
(d) roof bolters,
(e) rock duster, and
(f) miscellaneous.

However, the number of the above equipment that may be used in development of a panel depend on the rate of face advance, number of entries and headings, or more generally the total development production that will come from the panel.

The continuous mining units are highly versatile and can be used for other development or production works after completion of the development of a panel. Therefore, it is assumed that the capital investment in development equipment is proportional to the total production from the development works and the length of a panel.
where:

\[ \text{PID} = \text{DEINV} \times \text{PD} + M_3 \times Y \]  

**Capital Cost in Longwall Panel**

The equipment that will be needed for longwall production can be divided into three main groups:

1. powered cutters (shearers or plows),
2. roof support (frames, chocks, shields, chock-shields), and
3. conveyor system.

The equipment in a longwall unit can be further classified as:

1. Fixed capital cost items such as shearer, stage loader, etc. The cost of these items do not vary as the length of the face varies.
2. Linearly varying capital cost items such as roof support, face conveyor, belt conveyor, etc. The cost of these items vary linearly as the length of the face varies. And
3. Nonlinearly varying capital cost items such as face accessories, etc. The cost of these items vary nonlinearly as the length of the face varies. In this case the Sixth-Tenths factor is applied (see the footnote on page 19).
The capital cost of longwall panel is given as:

\[ C_1X + C_2X + C_3X^{0.6} + C_8Y + PI1 \]  

where:

- \( C_1 \): investment in roof support per linear foot of face length,
- \( C_2 \): investment in face conveyor per linear foot of face length,
- \( C_3 \): investment in nonlinear items per linear foot of face length,
- \( C_8 \): investment in belt conveyor per linear foot of panel length,
- \( PI1 \): investment in the fixed capital items.

**Total Capital Investment in a Longwall Panel**

The total capital investment in a longwall panel is the sum of the investment in the development and the panel equipment. This total capital investment (PI2) can be expressed as follows:

\[ PI2 = C_1X + C_2X + C_3X^{0.6} + C_8Y + PI1 + PID \]  

**Annual Depreciation**

Depreciation is a means of recovering investment in the equipment. Therefore the annual depreciation can be assumed as the annual cost of the equipment. Several methods can be used to calculate the annual depreciation. In this study, the straight line depreciation method is chosen because of the simplicity in its application. Furthermore, it is assumed that all the investment in a longwall panel qualifies for depreciation, and the equipment has a common useful life (n). Consequently, the annual depreciation can be expressed as
4.18 \[ D_p = \frac{P_{I2}}{n} \]

where:

\( D_p \) = annual depreciation,

\( P_{I2} \) = total capital investment in a longwall panel, and

\( n \) = useful life of the equipment.

4.322 Operating Cost Items

The operating costs of the production process can be classified into two categories; fixed and variable operating costs.

The fixed operating cost items are:

(i) Salaries and wages for personnel and supervision in both longwall and development units.

(ii) Power costs which include electricity and water.

(iii) Ventilation costs.

The variable operating cost items can be further subdivided into:

(i) Linear which include supplies for development and longwall production, installation and withdrawal, maintenance and service.

(ii) Nonlinear items which include indirect costs, such as indirect labor, supplies, overhead, etc. in production from the panel.

The annual operating cost equation is given as:

\[ TC = F_1 + C_7*(PAN) + C_6*PD + M_3*(PAN)^7 \]

where:

\( TC \) = annual operating cost,

\( F_1 \) = fixed cost for manpower, ventilation and power,

\( C_6 \) = fixed unit development production cost for supplies, labor, power, etc.,
$C_7 = \text{fixed unit panel production cost for supplies, maintenance and service, etc., and}$

$M_5 = \text{nonlinear cost for panel production.}$

**Total Annual Costs**

All the cost factors that have been grouped into capital cost, fixed cost, annual depreciation and operating cost can now be used to calculate the total yearly operating cost (TCC).

\[ TCC = Dp + TC \]

where:

- $TCC = \text{total annual cost,}$
- $Dp = \text{annual depreciation from Eq. 4.17, and}$
- $TC = \text{operating cost from Eq. 4.18.}$

The two major variables; production and cost can now be obtained from Equations 4.14 and 4.19 and will be used to formulate a cashflow equation and then also be applied to the four different objectives.

### 4.33 Cashflow Function

The cashflow function is required for the evaluation of some of the previously mentioned objectives. This function is equal to after tax income (exclusive of depreciation and depletion) plus the depreciation and depletion tax shield.\(^1\)

\[ \text{Cashflow function may include several other items, such as deferred exploration and predevelopment charges, interest and outstanding loans, taxable loss carried forward, etc. However, the above given simple form is considered adequate for the purpose of this study.} \]
Revenue

- Total operating costs
- Depreciation
- Depletion

Taxable Income

- Taxes

After tax income
+ Depreciation
+ Depletion

Cashflow

Alternatively:

\[ CF = (P \times PT - TC - Dp - DL)(1 - T) + (Dp + DL) \]

where:

\[ CF = \text{cashflow}, \]
\[ P = \text{unit price of the coal}, \]
\[ PT = \text{annual production}, \]
\[ TC = \text{total annual operating costs}, \]
\[ T = \text{tax rate}, \]
\[ Dp = \text{annual depreciation, and} \]
\[ DL = \text{annual depletion}. \]

or, assuming 50 percent tax rate

\[ CF = 0.5(P \times PT - TC + Dp + DL) \]
4.4 Formulation of the Problem

The problem of finding an optimal set of dimensions for a longwall panel may be formulated as a decision model by establishing the relationships between the objectives and the variables involved. This may be expressed in general terms as an unconstraint maximization problem.

Find X and Y such that

\[ \text{Max } F_i(X, Y) \]

In this formulation the X and Y denote the width and length of a longwall panel and the \( F_i(.) \) is the objective function of the decision maker expressed in terms of X and Y.

The detailed mathematical formulation of the problem according to the four previously mentioned objectives is given in the following sections.

4.4.1 Minimize Average Unit Cost

A decision maker may be interested in the dimensions of a longwall mining face which minimize the average unit cost. In the previous section, the total annual production (PT) and total annual cost (TCC) equations are formulated. In order to calculate the average unit cost, the total annual cost is divided by the total annual production.

\[ \text{UC} = \frac{TCC}{PT} \]

where:

\( \text{UC} = \) average unit cost,

\( \text{TCC} = \) total annual cost, and
PT = total annual production.

The above equation can be rewritten by using Equations 4.19 and 4.14 as

$$\text{UC} = \frac{\text{PI}^2 + \text{TC}}{\text{PT}}$$

where:

$$\text{PI}^2 = C_1 \times x + C_2 \times x + C_3 \times x^{0.6} + C_6 \times y + \text{PI1} + \text{PID},$$

$$\text{TC} = F_1 + C_7 \times \text{PAN} + C_6 \times \text{PD} + M_5 \times (\text{PAN})^{0.7}$$

n = useful life of the equipment, and

PT = total annual production.

4.42 Maximize Internal Rate of Return

The second objective is to find the optimum dimensions of a long-wall panel which maximize the internal rate of return of the investment in the panel. The internal rate of return (IRR) of a project is that rate of interest which discounts future net cash flows to the present value which in turn is equal to the present value of capital investment in the project. The net cash flow is defined as the difference between cash inflow and cash outflow for any given time period. The following is a general formula for the calculation of the internal rate of return of a project.

$$0 = \sum_{t=1}^{N} \text{CF}_t (1 + r)^{-t} - \text{PVI}$$

where:

$$\text{CF}_t = \text{net cash flow at time period t},$$

r = internal rate of return,

PVI = present value of initial investment, and

N = cashflow generating life of the project.
In other words r is an interest rate such that the present worth of project at that rate is equal to zero. By using the Equation 4.21 and assuming that (1) the entire capital investment in the development works and the panel qualify for depreciation, (2) the straight line depreciation method, and (3) a depletion allowance of 10 percent of the annual revenue:

\[
PVI = 0.5 \sum_{i=1}^{Z} \frac{(PT \times P - TC + \frac{PI2}{Z} + 0.1 \times P \times PT)/(1 + R)^Z}{Z} 4.23
\]

where Z is defined as a time period during which the same longwall panel equipment will be used in the production process.

\[
Z = \frac{750 \times N_1}{N_3 \times N} 4.24
\]

where:

- \( N_1 \) = useful life of the longwall panel equipment in years,
- \( P \) = unit price of per ton run of mine coal, and
- \( PT, TC, N_3 \) and \( N \) have been defined previously.

4.43 **Maximize Profitability Index**

The profitability index as defined before is the ratio of the net present value of future cashflows to the present value of initial investment. Theoretically, the present value of cashflows can be expressed as:

\[
PV = 0.5 \sum_{i=1}^{Z} \frac{(PT \times P - TC + \frac{PI2}{Z} + 0.1 \times P \times PT)/(1 + RCAP)^Z}{Z} 4.25
\]

where PV is present value of cashflows, RCAP is the cost of capital, PT, TC, P and Z already defined.
Then, the profitability index (PI) is given as:

\[ PI = \frac{PV - PI^2}{PI^2} \]

or

\[ PI = \frac{PV}{PI^2} - 1 \]  \hspace{1cm} 4.26

4.44 **Minimize Present Value of Average Unit Cost**

The fourth objective in this research is to find the optimum dimensions of a longwall panel which minimizes the present value of average unit cost. The annual costs which are the sum of the annual operating costs and fifty percent of the annual depreciation (considering the income tax shield) are discounted by the cost of capital in order to obtain the present value of the total cost (PVCOST).

\[ PVCOST = \sum_{i=1}^{Z} \frac{TC + 0.5*Dp}{(1 + RCAP)^i} \]  \hspace{1cm} 4.27

where the terms TC, RCAP, Dp and Z have been defined before.

The present value of average unit cost (PVUC), is given as the present value of the total cost divided by total production in those years. This is given as:

\[ PVUC = \frac{PVCOST}{PT*Z} \]  \hspace{1cm} 4.28

All the terms have been previously defined.
4.5 Solution of the Problem

An attempt is made to solve Equations 4.22, 4.23, 4.26 and 4.28 by the use of numerical techniques. The first and second partial derivatives are derived with respect to X and Y.

The solutions with respect to Y are monotonically decreasing or increasing depending on the objective. Secondly, the partial derivatives contained second order or higher order variables and the solution of these equations was very cumbersome. Therefore, the approach by analytical techniques was disregarded.

In order to solve Equations 4.22, 4.23, 4.26 and 4.28 numerical methods are used. The optimum values of face length (X) are obtained by solving the above equations. These optimum values of X are monotonically decreasing or increasing as panel length (Y) varies depending on the objective. Because of this, it is concluded that the panel length (Y) is not a critical variable, in optimization process. Consequently a simple computer program is used to solve the equations only for the face length X for fixed values of the panel length (Y).
In this chapter the problem is solved by assigning numerical values to the variables in the four different objectives and by using the models developed in Chapter IV. The numerical values are used as follows.

5.1 Production

Production comes from both development works and longwall panel. The numerical values in Table 1 are applied to Equations 4.1 through 4.13 to evaluate Equation 4.14. Consequently, production from the development works and the longwall panel are obtained as a function of panel dimensions X and Y.

5.2 Costs

The cost variable consists of capital costs and operating mining costs. As discussed in Chapter IV the cost items may be fixed, or vary linearly or nonlinearly with respect to the dimensions of a longwall panel. These costs are calculated by using information obtained from personal communication and from publications. In the cases where such cost items were obtained from literature a factor of twenty percent has been applied to allow for inflation. These costs are calculated as follows:
Table 1. Numerical Values Used in Production

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Assumed Numerical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_1$</td>
<td>Width of a heading</td>
<td>25 ft.</td>
</tr>
<tr>
<td>$W_2$</td>
<td>Distance between breakthroughs</td>
<td>75 ft.</td>
</tr>
<tr>
<td>$W_3$</td>
<td>Width of a breakthrough</td>
<td>25 ft.</td>
</tr>
<tr>
<td>$W_4$</td>
<td>Width of longwall face</td>
<td>30 ft.</td>
</tr>
<tr>
<td>$W_5$</td>
<td>Width of a pillar or distance between headings</td>
<td>50 ft.</td>
</tr>
<tr>
<td>$H$</td>
<td>Seam height</td>
<td>6 ft.</td>
</tr>
<tr>
<td>$D$</td>
<td>Density of coal</td>
<td>0.044 t/ft.$^3$</td>
</tr>
<tr>
<td>$Y$</td>
<td>Length of panel</td>
<td>5000 ft.</td>
</tr>
<tr>
<td>Longwall Unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{mf}$</td>
<td>Velocity of shearer in forward direction</td>
<td>20 ft./min.</td>
</tr>
<tr>
<td>$V_{mb}$</td>
<td>Velocity of shearer in backward direction</td>
<td>20 ft./min.</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Velocity of conveyor</td>
<td>220 ft./min.</td>
</tr>
<tr>
<td>$K$</td>
<td>Constant for direction of travel</td>
<td>±1</td>
</tr>
<tr>
<td>$a$</td>
<td>Maintenance and service time</td>
<td>0.04 min./ft.</td>
</tr>
<tr>
<td>$H$</td>
<td>Seam height</td>
<td>6 ft.</td>
</tr>
<tr>
<td>$S$</td>
<td>Conveyor capacity</td>
<td>0.040 t/ft.</td>
</tr>
<tr>
<td>$R$</td>
<td>Recovery factor</td>
<td>0.95</td>
</tr>
<tr>
<td>$TA$</td>
<td>Shift available time</td>
<td>300 min.</td>
</tr>
<tr>
<td>$A$</td>
<td>Width of rib pillar</td>
<td>50 ft.</td>
</tr>
<tr>
<td>$L$</td>
<td>Time required to make a change in direction and allowance for unscheduled delays and breakdowns</td>
<td>30 min.</td>
</tr>
</tbody>
</table>
5.21 **Capital Cost of Development**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Miner</td>
<td>1</td>
<td>400,000</td>
</tr>
<tr>
<td>Shuttle Car</td>
<td>2</td>
<td>200,000</td>
</tr>
<tr>
<td>Loader</td>
<td>1</td>
<td>120,000</td>
</tr>
<tr>
<td>Roof Bolter</td>
<td>1</td>
<td>100,000</td>
</tr>
<tr>
<td>Rock Duster</td>
<td>1</td>
<td>80,000</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td>180,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>$1,100,000</strong></td>
</tr>
</tbody>
</table>

It is assumed that production from the above equipment will be 350 tons per shift, the development equipment will be operating for 3 shifts a day and 220 shifts a year. Therefore the total production will be 230,000 tons in a year. Consequently, the amount of development investment required to generate a production capacity of one ton per year is $5. Further, assuming an average useful life of 5 years for these equipment, the annual capital cost of the equipment (DEINV) can be calculated as $1 per ton of development production.

In order to calculate the total capital cost for development (PID), the value of DEINV has to be substituted in Equation 4.15. The value of $M_3$, the investment in transportation equipment, is $25/\text{ft.}$, PD and $Y$ have been previously calculated.

\[
\text{PID} = \text{DEINV} \times \text{PD} + M_3 \times Y
\]  

4.15
5.22 **Capital Cost of Longwall Equipment**

The numerical values used in estimation of the longwall equipment costs are given in Table 2. The most of the figures in the table are based on a recent publication \(^{(44)}\) and updated in a few cases. These numerical values are then substituted into Equation 4.16 in order to find the total equipment costs (LEC) of a longwall panel in terms of its dimensions. This equation is

\[
LEC = C_1 X + C_2 X + C_3 X^{0.6} + C_4 Y + P11
\]

5.23 **Operating Costs**

The operating costs of a longwall panel are calculated in the following groups: manpower, maintenance and service, ventilation, supplies, installation and withdrawal, and power. These costs are then tabulated in Table 4 and used in Equation 4.18.

5.23.1 **Manpower Costs**

A survey of literature shows varied numbers of personnel are used at the face. Savidge \(^{(45)}\) wrote that his company used 11 men on each face: one shearer operator, one snaker on the conveyor, three men on the chocks, one man at each end of the face, one mechanic and two utility men. A face foreman was also used.

Jones\(^{(6)}\) stated an average of nine or ten men per shift as follows: foreman, mechanic, plow operator, tail end man, head end man and four propmen; the tenth man is optional and could be a tail end helper.
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Description</th>
<th>Parameter</th>
<th>Value ($)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shearer</td>
<td>Fixed investment</td>
<td>PIL</td>
<td>1,200,000</td>
<td>$/panel</td>
</tr>
<tr>
<td>Switch gear</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gear head ram</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power cables</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shearer monitor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage loader</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage loader accessories</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tools</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield (on 5-foot centers)</td>
<td>Linear with face length X</td>
<td>C₁</td>
<td>6,000</td>
<td>$/ft.</td>
</tr>
<tr>
<td>Chain face conveyor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36 in.-rope type conveyor for</td>
<td>Linear with panel length Y</td>
<td>C₈</td>
<td>90</td>
<td>$/ft.</td>
</tr>
<tr>
<td>main and production heading</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic power pack</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bretby</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic props</td>
<td>Nonlinear with face length X</td>
<td>C₃</td>
<td>5,000</td>
<td>$/ft.</td>
</tr>
<tr>
<td>Face accessories</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telephone and lines</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor motors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this study ten men are used on the longwall face as follows: foreman, one shearer operator, one helper, one headgate man, one mechanic, one utility man and one tailgate man, and three face men. A team of nine men are used on the development equipment unit. The wages for hourly personnel is from the National Bituminous Coal Wage Agreement of 1978. The cost per employer is calculated as $160/shift including union welfare, holiday allowance, and bonus. In the case of the annual salary of the face foreman thirty thousand dollars is used.

5.232 Maintenance and Service

It is assumed that routine maintenance will be done during the shift by the shift mechanic. When equipment is to be moved from one panel to the other, major repairs will be done after dismantling any face equipment. The time required for maintenance is incorporated into the cycle time.

5.233 Ventilation Costs

There is not much information about air requirements and face length. However, following Aman, it is assumed that the longwall ventilation requirement consists of two parts, a fixed part and another that varies with length of face. The volume of air $Q_1$ in Cfm needed is given as

$$Q_1 = 20,000 + \frac{4000}{100} \times x$$  \hspace{1cm} (5.1)
For a 500 ft. face $Q_{1}$ is calculated as

$$Q_{1 \, 500} = 30,000 + \frac{4000}{100} \times 500 = 50,000 \text{ Cfm}$$

The power requirement for the face is given by the following equation in horsepower

$$\text{POWER} = \frac{5 \times 10^{-13} \times (Q_{1})^{3}}{6350} \times \eta$$

5.2

The cost of power for the fans at 2¢ per kwh is given in dollars per foot as

$$\text{COSTS} = \frac{5 \times 131 \times 10^{-13} \times (Q_{1})^{3}}{6350 \times \eta} \times \eta$$

where $\eta$ is efficiency of the fan.

With this the annual power cost for a 500 ft. face length and an efficiency of 0.8 is calculated as

$$\text{COSTS} = \frac{131 \times 5 \times 10^{-13} \times (50,000)^{3}}{6350 \times 0.8} \times 500$$

$$= \$805.86 \text{ per year.}$$

However, the above cost is very small as compared to other cost items. Therefore the ventilation cost has been assumed as one of the fixed cost items.
5.234 **Installation and Withdrawal**

The number of shifts required to move the equipment from an old face and to install it in a new face varies from one face to another and from one mine to another. The factors that influence this number include skill of workers, seam height, face length and equipment. Generally, this number varies from 30 to 100 shifts.

In this study the number of shifts necessary for moving and installations \((N_4)\) is estimated as 10 shifts for preparation work and plus 15 shifts for per 100 feet of face length. Therefore

\[
N_4 = 10 + 15 \times \frac{X}{100}
\]

5.235 **Power Cost**

Electricity and water will be needed for both development and longwall units. Only a detailed electric requirement of the longwall unit is given. The power requirement of the development works are considered within fixed portion of unit development costs. Water consumption is assumed to be 6000 gallons per longwall unit per shift.

**Electrical Supply for Longwall Unit**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Horsepower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-Ended Ranging Shearer</td>
<td>580</td>
</tr>
<tr>
<td>EDW 340-LH</td>
<td></td>
</tr>
<tr>
<td>Motor Rating ((2 \times 170 \text{ kw}))</td>
<td>580</td>
</tr>
<tr>
<td>2 x 290 hp</td>
<td></td>
</tr>
<tr>
<td>Two Meco Conveyor Drive Heads with 120-hp motors</td>
<td>240</td>
</tr>
<tr>
<td>One 75-hp Westfalia Stage Loader</td>
<td>75</td>
</tr>
</tbody>
</table>
Table 3. Electricity and Water Costs

<table>
<thead>
<tr>
<th>Number of Units</th>
<th>Operation</th>
<th>Hp per Unit</th>
<th>Total Load</th>
<th>Kw Total Load</th>
<th>Hr per Day 60% Load</th>
<th>Total Energy (kwh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Longwall units</td>
<td>1310</td>
<td>1310</td>
<td>980</td>
<td>24</td>
<td>14,150</td>
</tr>
<tr>
<td>4</td>
<td>36-inch belt conveyor</td>
<td>100</td>
<td>400</td>
<td>300</td>
<td>24</td>
<td>4,320</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18,470</td>
</tr>
</tbody>
</table>

NOTE: (1) Annual consumption of electricity = $0.020 x 18,470 x 250 days/yr. = $92,350.

(2) It is assumed that longwall unit will consume 6000 gallons per unit per shift, and it costs $0.18 per 1000 gallons. The water cost is calculated as

\[ 6000 \times 3 \times 250 \times 0.18 = 810/\text{Yr.} \]
Table 4. Other Numerical Values Used in Hypothetical Problem

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Value Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed operating cost items of long-wall panel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manpower&lt;sup&gt;1&lt;/sup&gt;</td>
<td>$F_1$</td>
<td>$1,170,000</td>
</tr>
<tr>
<td>Electricity and water</td>
<td></td>
<td>93,160</td>
</tr>
<tr>
<td>Ventilation</td>
<td></td>
<td>810</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td>1,263,970</td>
</tr>
<tr>
<td>Fixed cost items of development production (labor, supplies, power, etc.)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>$C_6$</td>
<td>$6/ton</td>
</tr>
<tr>
<td>Fixed cost of panel production (supplies, maintenance and service)</td>
<td>$C_7$</td>
<td>$3/ton</td>
</tr>
<tr>
<td>Price of run of mine coal</td>
<td>$P$</td>
<td>$12/ton</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>RCAP</td>
<td>10</td>
</tr>
<tr>
<td>Nonlinear cost item for panel production&lt;sup&gt;3&lt;/sup&gt;</td>
<td>$M_5$</td>
<td>$145/ton</td>
</tr>
</tbody>
</table>

<sup>1</sup>Manpower cost calculation:

9 men/shift @ 3 sh/d * 250d/Y @ $160/shift + $90,000 for supervisors = $1,170,000.

<sup>2</sup>Labor cost is estimated as $4/ton.

<sup>3</sup>The annual panel production varies between 160,000 and 960,000 tons/Yr which depends on the face length. The annual cost of this nonlinear cost item varies between 200,000 to 560,000 $/Yr.
4. One 75-hp Westfalia Crusher

5. Two 75-hp Vickers hydraulic power packs for operation of
   the activated ramp plate

6. Three Dowty 50-hp hydraulic power packs for the roof
   support

7. Four 10-hp winches for retreating the stage loader

    TOTAL

The calculation of power cost and water cost is given in Table 3.

5.3. Solution of the Problem and Evaluation of the Results

The objectives mentioned in Chapter IV are solved by using the
numerical data developed in the previous section. As mentioned before
the idea of finding the optimum dimensions in two directions is dis-
carded. Because, the optimum values of face lengths (X) obtained by
solving the four different objectives are monotonically increased as
panel length (Y) increases. Therefore, it is concluded that the panel
length is not a critical variable, and its length should be limited by
operational constraints. Consequently, the panel length Y is fixed at
5000 feet and only the face length X is varied.

A simple fortran program is used to find the optimum values of X
under the four different objectives. These results are then used to
draw the graphs given in this section. The result of the minimization
of the average unit cost objective is shown in Figure 4. As it may be
seen from this figure, the minimum average unit cost lies in the range
of 450 to 550 feet of face length.
Figure 4. Average Unit Cost Versus Face Length
Figure 5 shows the graph of the maximization of Internal Rate of Return Objective versus the face length. The graph shows a relative maximum at a face length of about 270 feet.

The profitability index objective gives a result similar to the internal rate of return objective. Figure 6 shows a plot of profitability index against face length. The relative maximum is in the range of 340 feet.

The result of the minimization of the average unit cost objective is similar to that of the average unit cost objective. The graph of present value of unit cost in dollars per ton is plotted against the face length \(X\) in feet in Figure 7. The relative minimum is in the range of 720 feet.

5.4 Sensitivity Analysis of the Results

Sensitivity analysis is the means of evaluating the effects of uncertainty on the profitability of an investment proposal. Sensitivity analysis identifies the critical variables that, if changed, could affect the results significantly.

In carrying out a sensitivity analysis, individual variables are changed and the effect of such a change on the objectives are computed. Once all the critical variables have been identified, they can be given special attention by the decision maker. The variables varied in this study are initial investment, project life, cycle time, cost of capital, panel length and price of coal.

Figure 8 shows the effects of a change in investment on the optimum values of \(X\) under the four different objectives. Investment
Figure 5. Internal Rate of Return Versus Face Length

Internal Rate of Return

Face Length in Feet
Figure 6. Profitability Index Versus Face Length

Face Length in Feet

Profitability Index

0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3

0 300 600 900 1200
Figure 7. Present Value of Average Unit Cost Versus Face Length
Figure 8. Effects of a Change in Investment on Face Length
changes are made at ten percent intervals up to fifty percent. As the investment is increased the face lengths which correspond to the minima of the present value of the average unit cost objective and average unit cost objective decrease. However, no significant effect is seen in the internal rate of return and the profitability index.

Figure 9 shows the effects of a change in the life of the project on the face lengths which optimize the profitability index, the internal rate of return, the present value of average unit cost and the average unit cost objectives. Life of project changes are made at sixteen percent intervals up to a hundred percent. As the life of the project is changed the face lengths which correspond to minima of the present value of the average unit cost objective and average unit cost objective increase. However, no significant effect is seen in the internal rate of return and the profitability index. From Figure 9 we can conclude that the present value of average unit cost curve is too sensitive to the life of the project.

Figure 10 shows the effects of a change in cycle time on the optimum values of X under the four different objectives. Cycle time changes are made at ten percent intervals up to fifty percent. As the cycle time is increased the face lengths which correspond to minima of the present value of average unit cost objective and average unit objective decrease. However, no significant effect is seen in the internal rate of return and the profitability index.

Figure 11 shows the effects of a change in cost of capital on the optimum points in the profitability index objective and internal rate
Figure 9. Effects of a Change in Life on Face Length
Figure 10. Effects of a Change in Cycle Time on Face Length
Figure 11. Effects of a Change in Cost of Capital on Face Length
of return objective. Interest rate changes are made at five percent intervals up to twenty five percent. As the cost of capital is changed no significant change is seen in the internal rate of return and the profitability index.

Figure 12 shows the effects of a change in the panel length on the optimum values of X under the four different objectives. Panel length changes are made at 1000 feet intervals up to 5000 feet. As the panel length is increased the optimum values of X under the four different objectives increase.

Figure 13 shows the effects of a change in price of coal on the optimum points in the profitability index objective and internal rate of return objective. As the price of coal is increased the face lengths which correspond to the maximum of the internal rate of return objective decrease. However, there is no significant change in the profitability index objective.
Figure 12. Effects of a Change in Panel Length on Face Length
Figure 13. Effects of a Change in Price of Coal on Face Length
6.1 Conclusions

The result of the average unit cost objective gives an optimum face length in the range of 450 to 550 feet. However, the minimization of the average unit cost as an objective does not consider the productivity of capital invested in the project. Therefore, another decision maker may prefer some other yardsticks such as minimization of the present value of average unit cost, maximization of the profitability index, or maximization of the internal rate of return in measuring profit potential of an investment proposal.

The result of the present value of average unit cost objective gives result in the range of 720 feet.

The result of the profitability index objective gives optimum face lengths in the range of 340 feet.

The result of the internal rate of return objective gives optimum face lengths in the range of 270 feet.

The sensitivity analysis shows that the average unit cost objective is sensitive to change in investment, project life, cycle time, and the panel length. The internal rate of return objective is sensitive to the panel length and price of coal. The profitability index is only sensitive to the panel length. The present value of average unit cost objective is the most sensitive to change in investment, life of project, cycle time and the panel length.
6.2 Recommendations for Future Work

In this research, the analysis of the problem has been based on several assumptions. A natural extension of the problem is the relaxation of some of these assumptions to investigate their effects on the optimum dimensions of a longwall panel. For example:

(i) The research considers only economical aspects of the problem, but does not consider some possible technological limitations that may be imposed on the dimensions of a panel by the external factors such as geological and rock mechanical characteristics of the environment. For example, these factors may necessitate additional expenditures for more extensive and heavier supports as the dimensions vary. Their cost increasing effects, if known, can be added to the problem.

(ii) The assumption as to unlimited availability of investment funds at the same cost may be relaxed. Some budgetary constraints and different costs of capital for varying debt-to-equity ratios may be imposed.

(iii) The assumption as to the provision of other facilities and sources can be relaxed.

(iv) The assumption in manpower requirements can be relaxed and changed as the face length varies beyond certain limits.

(v) The opportunity cost of level of recovery can be added into the model and the effect tried on optimum dimensions of a longwall panel.
APPENDIX

GLOSSARY OF SYMBOLS
## GLOSSARY OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Width of rib pillar (ft)</td>
</tr>
<tr>
<td>a</td>
<td>Maintenance and service time per feet</td>
</tr>
<tr>
<td>C₁</td>
<td>Investment in roof support per linear foot of face length ($/ft)</td>
</tr>
<tr>
<td>C₂</td>
<td>Investment in face conveyor per linear foot of face length ($/ft)</td>
</tr>
<tr>
<td>C₃</td>
<td>Investment in nonlinear items per foot of face length ($/ft)</td>
</tr>
<tr>
<td>C₆</td>
<td>Fixed cost items of development production (for labor, supplies, power, etc.) ($/ton)</td>
</tr>
<tr>
<td>C₇</td>
<td>Fixed cost of panel production (for supplies, maintenance and service) ($/ton)</td>
</tr>
<tr>
<td>C₈</td>
<td>Investment in belt conveyor per linear foot of panel length ($/ft)</td>
</tr>
<tr>
<td>CF</td>
<td>Cashflow ($)</td>
</tr>
<tr>
<td>D</td>
<td>Density of coal (tons/ft³)</td>
</tr>
<tr>
<td>DEINV</td>
<td>Capital investment per ton of production ($/ton)</td>
</tr>
<tr>
<td>DL</td>
<td>Annual depletion (percentage)</td>
</tr>
<tr>
<td>Dp</td>
<td>Annual depreciation ($/year)</td>
</tr>
<tr>
<td>d₁</td>
<td>Depth of forward cut (ft)</td>
</tr>
<tr>
<td>d₂</td>
<td>Depth of backward cut (ft)</td>
</tr>
<tr>
<td>Fᵐ</td>
<td>Fixed cost for manpower ($/yr)</td>
</tr>
<tr>
<td>H</td>
<td>Seam height (ft)</td>
</tr>
<tr>
<td>K</td>
<td>Constant factor for direction of travel (+1)</td>
</tr>
<tr>
<td>L</td>
<td>Time required to make a change in direction and allowance for unscheduled delays and breakdown (min)</td>
</tr>
<tr>
<td>LEC</td>
<td>Longwall equipment cost ($)</td>
</tr>
<tr>
<td>M₁</td>
<td>A constant factor with face length</td>
</tr>
<tr>
<td>M₂</td>
<td>A constant removal and preparation time</td>
</tr>
<tr>
<td>M₃</td>
<td>Investment in transportation equipment ($/ft)</td>
</tr>
<tr>
<td>N₅</td>
<td>Nonlinear cost for panel production ($/ton)</td>
</tr>
<tr>
<td>N'</td>
<td>Number of headings in an entry</td>
</tr>
<tr>
<td>n</td>
<td>Useful life of equipment (years)</td>
</tr>
<tr>
<td>N₁</td>
<td>Useful life of the longwall panel equipment in years</td>
</tr>
<tr>
<td>N²</td>
<td>Number of panels to be mined in a year</td>
</tr>
<tr>
<td>N₃</td>
<td>Number of shifts to mine coal from a panel</td>
</tr>
<tr>
<td>N₄</td>
<td>Installation and withdrawal shifts</td>
</tr>
<tr>
<td>P</td>
<td>Unit price of per ton run of mine coal ($/ton)</td>
</tr>
<tr>
<td>PAN</td>
<td>Annual production from a longwall panel (ton/yr)</td>
</tr>
<tr>
<td>Pb</td>
<td>Production from breakthroughs (ton)</td>
</tr>
<tr>
<td>PCYCLE</td>
<td>Production per cycle (ton)</td>
</tr>
<tr>
<td>PD</td>
<td>Total development production (ton)</td>
</tr>
<tr>
<td>Pf</td>
<td>Production from face (ton)</td>
</tr>
<tr>
<td>Ph</td>
<td>Production from heading</td>
</tr>
<tr>
<td>PI</td>
<td>Profitability index</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>PID</td>
<td>Total capital cost for development ($)</td>
</tr>
<tr>
<td>PI1</td>
<td>Investment in the fixed capital items ($)</td>
</tr>
<tr>
<td>PI2</td>
<td>Total capital investment in a longwall panel ($)</td>
</tr>
<tr>
<td>PSHIFT</td>
<td>Production per shift (ton)</td>
</tr>
<tr>
<td>PT</td>
<td>Total annual production (ton)</td>
</tr>
<tr>
<td>PV</td>
<td>Present value of cashflow</td>
</tr>
<tr>
<td>PVCOST</td>
<td>Present value of cost</td>
</tr>
<tr>
<td>PVUC</td>
<td>Present value of average unit cost</td>
</tr>
<tr>
<td>PVI</td>
<td>Present value of initial investment</td>
</tr>
<tr>
<td>R</td>
<td>Level of recovery (percent)</td>
</tr>
<tr>
<td>RCAP</td>
<td>Cost of capital (percent)</td>
</tr>
<tr>
<td>r</td>
<td>Internal rate of return (percent)</td>
</tr>
<tr>
<td>Rp</td>
<td>Recoverable coal reserves in a panel (ton)</td>
</tr>
<tr>
<td>S</td>
<td>Conveyor capacity (ton/ft)</td>
</tr>
<tr>
<td>T</td>
<td>Tax rate</td>
</tr>
<tr>
<td>TA</td>
<td>Shift available time (min)</td>
</tr>
<tr>
<td>TC</td>
<td>Annual operating cost ($)</td>
</tr>
<tr>
<td>TCC</td>
<td>Total annual cost ($)</td>
</tr>
<tr>
<td>TCYCLE</td>
<td>Cycle time</td>
</tr>
<tr>
<td>Tpc</td>
<td>Cycle time (min)</td>
</tr>
<tr>
<td>UC</td>
<td>Average unit cost ($/ton)</td>
</tr>
<tr>
<td>Vmb</td>
<td>Velocity of shearer in backward direction (fpm)</td>
</tr>
<tr>
<td>Vc</td>
<td>Velocity of conveyor (fpm)</td>
</tr>
<tr>
<td>Vmf</td>
<td>Velocity of shearer machine in forward direction (fpm)</td>
</tr>
<tr>
<td>W1</td>
<td>Width of a heading (ft)</td>
</tr>
<tr>
<td>W2</td>
<td>Distance between breakthroughs (ft)</td>
</tr>
<tr>
<td>W3</td>
<td>Width of breakthrough (ft)</td>
</tr>
<tr>
<td>W4</td>
<td>Width of longwall face (ft)</td>
</tr>
<tr>
<td>W5</td>
<td>Width of pillar (ft)</td>
</tr>
<tr>
<td>X</td>
<td>Face length (ft)</td>
</tr>
<tr>
<td>Y</td>
<td>Longwall panel length (ft)</td>
</tr>
<tr>
<td>Z</td>
<td>Time period during which the same longwall panel equipment will be used in the production process</td>
</tr>
</tbody>
</table>
REFERENCES


30. Jackson, Dan, "Advancing Longwall Mining: A First for Midcontinent Coal and a First for the U.S.", Coal Age, Vol. 80, No. 9, September 1975, p. 103.


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AN OPTIMAL DETERMINATION OF LONGWALL PANEL DIMENSIONS

by

Okechukwu Onyebuchi Onyemaobi

(ABSTRACT)

The optimal dimensions of a longwall panel are investigated using four different objectives of minimum average unit cost, internal rate of return, profitability index and present value of average unit cost. The two main variables, production and cost are analyzed into different parameters. Production and cost equations are developed and the four different objectives are expressed in the form of equations. These equations are solved and the plots of the results are included. A sensitivity analysis of the results is made by changing initial investment, project life, cycle time and cost of capital. If the objective of the decision maker is to minimize average unit cost, the optimum dimension of the longwall coal mining face in this study is in the range of 450 to 550 feet.