

**SELECTING WIRE ROPE DESIGN FACTORS IN CABLE YARDING**

**A REVIEW AND PROPOSAL**

by

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A PAPER

submitted to

Oregon State University

in partial fulfillment of the  
requirements for the degree of

Master of Forestry

Completed April, 1992

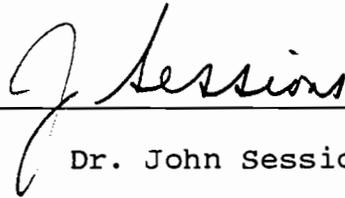
Commencement June, 1992

AN ABSTRACT OF THE PAPER OF

Steven J. Rheinberger for the degree of Master of Forestry  
in Forest Engineering presented on March 29, 1992.

Title: Selecting Wire Rope Design Factors In Cable Yarding  
A Review And Proposal.

Abstract Approval:



Dr. John Sessions

Traditional rationale for design factors is briefly reviewed. Methodologies for determining these traditional design factors are lacking and are usually based upon subjective reasons which result in applying a design factor of 3.0 in all cases (western United States).

Factors which affect wire rope life are discussed. These factors include steel properties (i.e. elastic limit), rope construction, types of loading (static and impact), bending stress, fatigue, wire rope maintenance, line length, line use, and expected life.

Historically, the logging industry has not explicitly considered the economics of harvesting in selecting a design factor for harvest planning. Maximizing the service life of the wire rope may not maximize profit or minimize yarding costs. When cable yarding is considered, log production is a very important factor. The net

payload which can be transported to the landing and the speed of the transport determine, to a large extent, the hourly production rate. In order to maximize production it is often necessary to operate at high line tensions. Although wire rope used in such a manner must be replaced more often (shorter life), work is accomplished which cannot be performed by any other means for the same cost. This paper presents a procedure for applying a design factor based on yarding costs.

Since the planning of most skyline harvest systems starts with some design factor for the determining maximum tensions which can be used on a particular profile, the economic approach for determining a design factor seems like a reasonable strategy. To the operator of a cable yarding system, this strategy may be more appropriate than applying a design factor of 3.0 in all cases. Finding the optimum payload (or range of payloads) which minimizes overall yarding costs is a sound strategy for planning skyline harvest systems.

The procedure in this report uses a yarding simulation model to determine yarding production, wire rope tensions, wire rope lives, and yarding cost per unit volume. The simulation was done on a hypothetical timber stand with a running skyline system. Line lives were determined by accumulating the proportion of line life used as each turn was yarded. The number of bends until failure was used as a yardstick for determining line life. Yarding cost per unit volume was then compared as logloads were increased until

a minimum cost was identified. Design factors for both the mainline and skyline for each average logload were calculated and compared.

The results of the simulation indicated that applying a design factor of 3.0 may not be appropriate when considering the effects of the design factor on yarding costs.

Crew safety was not considered implicitly in the procedure. However, modifications of the procedure to include crew safety are discussed.

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# SELECTING WIRE ROPE DESIGN FACTORS IN CABLE YARDING

## A REVIEW AND PROPOSAL

### INTRODUCTION

The purpose of a design factor (factor of safety) for wire rope is to provide for an economic and safe operation for the rope.

Planning for and appraising cable yarding timber sales begins with a selection of a design factor. The design factor is used to establish the maximum design tension, where the maximum design tension is calculated by dividing the breaking strength of new wire rope by the design factor. If a logload causes a tension which exceeds the design tension, the tension is considered unacceptable.

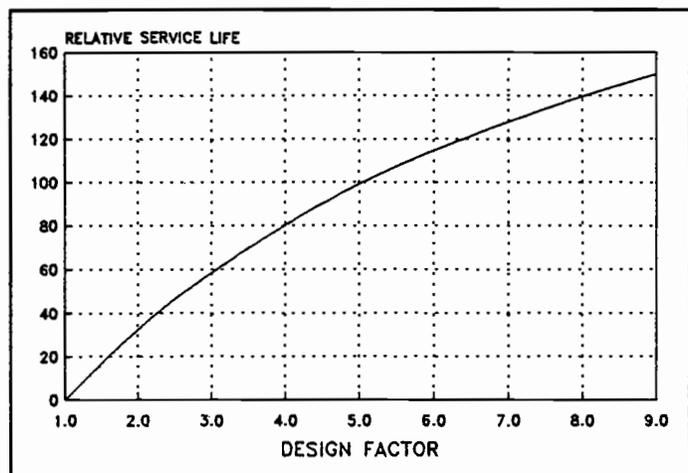
Wire rope can be thought of as a machine which tends to wear out with use. Similar to other parts of machines, wire rope has a finite life. A wire rope consists of wires woven into strands around a core. The wires are subject to abrasion, fatigue, and corrosion. The choice of an appropriate design factor keeps the ratio of the design tension to the breaking strength of new wire rope at an acceptable level.

Little documentation exists for the methodology for choosing an appropriate design factor. A design factor of 3.0 is typically used in the western United States and Canada. In Europe and

Scandinavia, design factors for cable logging range from 2.5 to 3.0 for lines which do not move (such as a standing skyline) and from 4.0 to 5.0 for moving lines (such as mainlines) [6].

Information as to the specific origin for determining these design factors is lacking. One commonly cited consideration is the relative service life of the rope [13]. The service life of a wire rope is defined as the length of time a particular rope can be used for a particular application. The design factor that is selected plays an important part in determining the service life of the rope (Figure 1).

Because of the higher tension the wire rope will be operating at relative to its breaking strength, a change in the design factor from 5.0 to 3.0 decreases the service life index of the rope from 100 to 60 - a drop of 40%.



**Figure 1. Relative Service Life Curve.** (Wire Rope Users Manual, 1981)

It seems useful to choose a design factor which recognizes the service life of the rope along with other factors such as log production at the landing, line replacement costs, and overall worker safety. Sessions and Pyles [7] used an approach which considered production, line costs, and

overall worker safety (an economic strategy) to determine the optimum design factor for a tailspar. This approach combined revenues, production, operating and safety costs to maximize net revenue. Based on the net revenue, optimal design factors were calculated.

## OBJECTIVES AND SCOPE

The objectives of this paper are to 1) review factors which affect wire rope life, and 2) propose a simulation method for choosing a design factor which incorporates economics of the yarding system. The simulation method for determining design factors will only consider static tensions. Static tensions involve forces which are not due to changes in velocity as the log is being yarded. Dynamic tensions, which involve positive or negative changes in velocity, will not be considered in the simulation method. Hang-ups, log breakout, and logs swinging free of the ground (in transition from partial to full log suspension) are considered examples of dynamic loads.

The main factors affecting rope life are the elastic limit, rope construction, tensions caused by static and dynamic loads, axial stresses, bending stresses, bending fatigue, rope maintenance, line use, and line length. Line uses can be categorized into areas such as moving lines and static lines (lines which do not move or are stationary during operation).

## ELASTIC STRETCH

Within limits, wire rope can be thought of acting like a linear spring. The range in which the rope will act like a linear spring has an upper limit known as the elastic limit. Within the elastic range (the elastic limit), wire rope can be stretched under tension and then returned to its original length and diameter when the tension is removed. When elastic stretch takes place, there is a linear relationship between stress and strain (EQ. 1) [2].

$$E = \frac{\sigma}{\epsilon} = \frac{\left(\frac{T}{A}\right)}{\left(\frac{dL}{L}\right)} \quad [\text{EQ. 1}]$$

Where: E = modulus of elasticity of the rope (psi)  
T = tension in the wire rope (lb)  
A = actual metallic cross sectional rope area (sq. in.)  
dL = amount of stretch under tension (in)  
L = unstretched rope length (in)  
 $\sigma$  = stress in rope (psi)  
 $\epsilon$  = strain in rope (in/in)

For wire rope used in cable yarding (commonly 6 X 19 class rope), the modulus of elasticity varies between 10 and 15 million psi depending upon the number of wires in each strand and the type of steel used [13]. A 6 X 19 wire rope contains 6 strands that are

made up of 9 to 26 wires, of which no more than 12 are outside wires [13].

If a wire rope is stretched beyond the elastic limit, it will become permanently stretched and will not return to its original length. The result is a small reduction in the original diameter of the rope at the weakest point in the rope and a permanent reduction in the overall tensile strength of the rope [2]. For wire rope commonly used in cable logging, the elastic limit is between 60% and 65% of the breaking strength of new wire rope [5]. In terms of design factors, the implication here is obvious. The elastic limit of the rope is an important element to consider. A design factor should not result in tensions exceeding the elastic limit. Design factors which consider the elastic limit of wire rope would be calculated as follows:

$$(\text{Design Tension})/(\text{Breaking Strength}) = .60 \text{ to } .65$$

or

$$(\text{Breaking Strength})/(\text{Design Tension}) = 1/.60 \text{ to } 1/.65$$

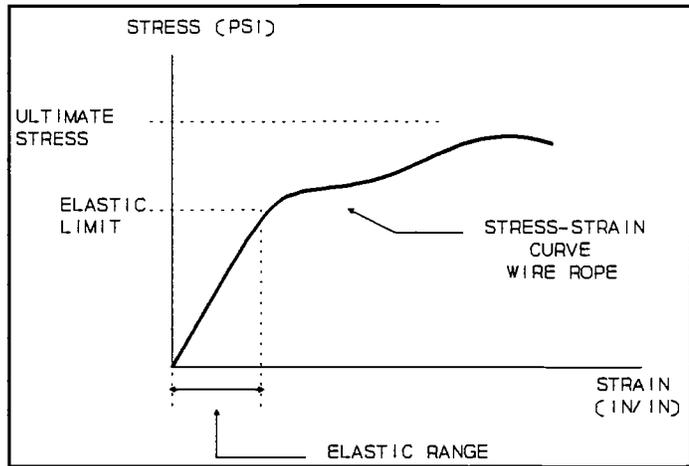
or

$$\text{Design Factor} = 1.67 \text{ to } 1.54$$

The elastic range can be seen in the stress-strain curve (Figure 2) [2]. The modulus of elasticity, E, is the slope of the curve over the elastic range (stress divided by strain).

A form of permanent stretch known as constructional stretch occurs

when a new wire rope is first put into service. The amount of this stretch is typically 0.25% to 0.75% of the original length of the rope and should not be confused with the discussion of elastic stretch [13].



**Figure 2. Stress-strain curve for a typical wire rope. (Gere, 1990)**

## ROPE CONSTRUCTION

Bending fatigue and abrasive wear are two major destructive forces on wire rope used in cable logging [13]. The type of rope construction greatly determines the degree to which the rope will resist these destructive forces. In most cases selecting a suitable wire rope which will resist all the destructive forces equally well is not feasible. For example, a rope which has relatively few outside wires is highly resistant to abrasive wear but is markedly less resistant to bending fatigue because of the resulting increased stiffness associated with fewer outside wires [13]. For these reasons a compromise must usually be made in the design and application of a wire rope for any specific operation. Most wire ropes used in cable logging are in the 6 X 19 class (6 strands with 9 to 26 individual wires per strand) with an independent wire rope core (IWRC) and reflect this compromise [12]. Ropes in the 6 X 19 class are resistant to abrasive wear but less resistant to bending fatigue than ropes in the 6 X 26 class because of the greater stiffness of individual wires in 6 X 19 wire rope [13].

## TYPES OF TENSIONS

Wire rope tensions during cable logging applications can be divided into two types: 1) static and 2) dynamic. Static tensions involve forces which are not due to changes in velocity as the log is being yarded. Dynamic tensions involve positive or negative changes in velocity. Hang-ups, log breakout, and logs swinging free of the ground (in transition from partial to full log suspension) are considered examples of dynamic loads. Breakout forces are the forces required to overcome log inertia.

Design factors include both of these tension types, either explicitly or implicitly. Static tensions are explicitly calculated by payload analysis techniques. Dynamic tensions have not commonly been explicitly included in the analysis of cable logging tensions due to their variable and unpredictable nature. The design factor is usually increased to include allowances for dynamic tensions.

## AXIAL STRESSES

Axial or normal stresses are created by forces directed along the axis of the rope. Axial stress is equal to the ratio of the tension in the wire rope to the actual metallic area of the wire rope (EQ.2) [2]. The breaking strength of wire rope is determined by its tensile strength.

$$f_a = \frac{T}{A} \quad \text{[EQ. 2]}$$

Where:     fa = axial stress (psi)  
          T = the tension in rope (lb)  
          A = actual metallic cross sectional rope area (sq.  
          in.)

## BENDING STRESSES

Bending stresses in cable logging take place when wire rope is bent around sheaves or drums. Exact formulas to predict the magnitude of these stresses are not known due to the complexity and interaction of individual wires in the rope [5]. The Roebling Wire Rope Handbook gives eight equations for estimating bending stress. The equation most frequently used in the literature and which predicts the largest value for bending stress is also the simplest (EQ. 3) [5].

$$f = \frac{(E*d)}{D} \quad [\text{EQ. 3}]$$

Where:     f = bending stress (psi)  
           E = modulus of elasticity for rope (psi)  
           d = diameter of outside wire (in)  
           D = diameter of sheave (in)

The maximum and minimum combined stress in the wire rope is the sum or difference of the normal stress and bending stress depending on the side of the bend.

$$f_t = f_a \pm f_b \quad [\text{EQ. 4}]$$

Where:     ft = total axial stress (psi)  
           fa = axial stress - T/A (psi)  
           fb = bending stress (psi)

When a wire rope is bent around a sheave, the redistribution of stresses must be considered to prevent excessive combined stress on the outside of the bend. The design tension on the rope must be reduced to reflect these combined stresses. This reduction of design tension is directly related to

radius of the bend the rope makes over the sheave or drum.

The smaller the radius, the greater the bending stress.

The ratio of the reduced design tension to the design tension without bends is called the strength efficiency (Figure 3) [3]. To obtain 95% strength efficiency, the ratio must be 30 times the rope

diameter. For 1-inch wire rope this would require a 30-inch sheave. This sheave size is usually not practical for cable yarding situations because of weight limitations and transport difficulties to remote areas. A typical running skyline operation may have a haulback block around 12 inches in diameter.

| <u>Sheave/Rope Diameter Ratio</u> | <u>Efficiency Of Rope **</u> |
|-----------------------------------|------------------------------|
| 10 times                          | 79%                          |
| 12 times                          | 83%                          |
| 14 times                          | 86%                          |
| 16 times                          | 88%                          |
| 18 times                          | 90%                          |
| 20 times                          | 91%                          |
| 24 times                          | 93%                          |
| 30 times                          | 95%                          |

\*\* Strength rope over sheave / strength straight rope

**Figure 3. Strength Efficiency Under Static Load. (Miles, 1978)**

## BENDING FATIGUE

Bending fatigue results from repeated cycles of stress and strain, causing a deterioration of the material and resulting in progressive cracking that eventually produces failure [2]. One way to describe this type of stress is to think of bending a paper clip. If it is bent repeatedly back and forth, it will eventually break. To a certain extent, the same thing happens to a wire rope when it is bent repeatedly around sheaves and drums. Failure may occur even if stresses never exceed the elastic limit of the wire rope.

Small sheaves can cause wire rope to fatigue earlier than larger sheaves with all other factors being equal [1,3]. A major factor influencing fatigue life is the sheave bearing pressure. Sheave bearing pressure is a measure of pressure exerted by the wire rope as it passes around a sheave (EQ. 5) [13].

$$p = \frac{(2 * T)}{(d * D)} \quad \text{[EQ. 5]}$$

Where:    p = sheave bearing pressure (psi)  
          T = rope tension (lb)  
          d = rope diameter (in)  
          D = sheave diameter (in)

Drucker and Tachau [1] found a strong correlation between the bearing pressure ratio, B (EQ. 6), and wire rope life (bends to failure).

$$B = \frac{p}{U} = \frac{2 * T}{U * d * D}$$

[EQ. 6]

Where: B = bearing pressure ratio (dimensionless)  
 U = ultimate tensile stress in the wire (psi)  
 p = sheave bearing pressure (psi)

Laboratory tests conducted on various classes of wire ropes by Drucker and Tachau resulted in a well-defined curve which relates "B" (bearing pressure ratio) and the number of bends to failure, "N" (Figure 4) [1]. Wire ropes of different diameters and construction follow a similar pattern [1].

Example:

A 7/8-inch wire rope passing over a 16-inch sheave at 23,000 pounds of tension will have a bearing pressure ratio, B, of .0137. This "B" would give an approximate wire rope life of 8,000 bends to failure. Increasing sheave diameter can greatly increase rope life by reducing the bearing pressure ratio.

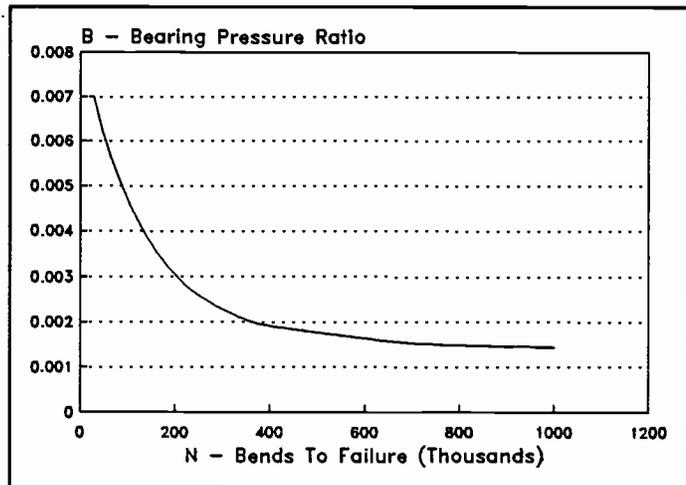


Figure 4. Bearing Pressure VS Life of a 6 X 19 Wire Rope. (Drucker, 1945)

During skyline yarding log inhaul, wire rope is subject to tensions

of variable magnitude over the span of the yarding system. The rope life, in terms of bends until failure (Figure 4), also varies for each different tension the wire rope is subjected to during log inhaul. As the tension (and rope life) varies from point to point along the span of the yarding system, the combined result for the line life can be determined.

The fractions of line life used up at several given tensions will add up to unity (1) at failure (EQ. 7) [17].

$$\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \dots = 1 \quad \text{[EQ. 7]}$$

Where:  $N_1, N_2, N_3$  = wire rope life (bends until failure) at tensions 1, 2, 3... (Figure 4)

The "cumulative damage" equation summarizes the result [17].

$$\sum_{i=1}^k \frac{1}{N_i} = 1 \quad \text{[EQ. 8]}$$

Where:  $N_i$  = wire rope life (bends until failure) at varying tensions, i to k

EQ. 8 can be used to determine the proportion of the line life expended to yard a particular area or corridor. Since the fraction of line life used up (for a particular section of line) at each tension along the span of the yarding system during log inhaul is equal to the reciprocal of the corresponding line life, the amount of line life used for the corridor is obtained with EQ. 9.

$$FL = \sum_{i=1}^n \frac{1}{N_i} \quad [\text{EQ. 9}]$$

Where:  $N_i$  = wire rope life (bends until failure) at varying tension (Figure 4),  $i$  to  $n$ , over the corridor or area to be yarded (provided failure has not occurred)  
 $FL$  = proportion of the wire rope life used up to yard the corridor or area

## WIRE ROPE MAINTENANCE

Wire rope requires periodic maintenance in order to perform to its potential. As the rope is simultaneously stressed axially and bent over sheaves, the individual wires and strands slide over and press against each other. Like any other machine, these moving parts need lubrication. Proper field lubrication at periodic intervals is vital to the life of wire rope.

The service life of wire rope can also be extended by switching ends of operating lines (skyline, mainline, haulback, and slackpulling) at various intervals. In many cases, the last several hundred feet of the cable yarding rope is stored on the drum and never used. By switching ends, wear on the line will be more evenly distributed over the entire length of the wire rope.

All wire rope should be inspected periodically for signs of the following [13]:

- 1) rope diameter reduction
- 2) external wear
- 3) internal wear
- 4) peening - small cracks caused by continuous pounding
- 5) scrubbing - displacement of wires and strands as a result of rubbing against themselves or another object
- 6) corrosion
- 7) broken wires

By inspecting the rope, problems can be spotted and corrected before a more serious problem results. The operator who conducts regular maintenance on his wire rope can expect to have a longer rope life.

## LINE TYPE AND USE

A major consideration in determining an appropriate design factor is the specific use of the line. Should all lines on a cable yarding operation have the same factor of safety? It seems reasonable to assume that they should not. A line which is constantly run over sheaves and under high tension (relative to other lines not run over sheaves and at a lower tension) would appear to warrant a larger design factor than a line such as a guyline due to the bearing pressure and resulting fatigue (bends until failure).

For example, a running skyline system may consist of three lines: 1) the haulback, 2) the mainline, and 3) the guylines. One rational process for determining the maximum design tension for each type of line might consist of a series of tension reductions:

- 1) Reduction in tension for elastic limit (60%)
- 2) Reduction in tension from bending (Figure 3)
- 3) Reduction in tension for impact loads

The haulback and mainline, which are constantly run at high speeds, could be analyzed as follows:

- 1) Line size = 7/8-inch
- 2) Smallest sheave or drum size = 12-inch

- 3) Breaking strength of wire rope..... 79,500 lbs
- 4) Elastic limit =  $(0.40) * (79,500)$ .....-31,800 lbs  
 The factor 0.40, is  $(1-.60)$ . Where .60 47,700 lbs  
 is the elastic limit of the wire rope.
- 5) Reduction for efficiency to percent  
 excessive tension from bending  
 (from Figure 3) =  $12/.875 = 13.7$  times  
 $(0.14) * (47,700)$ .....-6,678 lbs  
 The factor .14, is  $(1-.86)$ . Where .86 41,022 lbs  
 is from Figure 3.
- 6) Factor for impact loads =  $(0.25) * (41,022)$ ...-10,255 lbs  
 The factor for impact loads, .25 30,767 lbs  
 is  $(1-.75)$ . Where .75 was chosen  
 arbitrarily.
- 7) Maximum design tension..... 30,767 lbs
- 8) Implied design factor =  $79,500/30,767$ ..... 2.6

The guylines, which remain static, could be analyzed as follows:

- 1) Line size = 1-1/4 inch
- 2) Breaking strength..... 159,800 lb
- 3) Elastic limit =  $(0.40) * (159,800)$ .....-63,920 lbs  
 95,880 lbs
- 4) Factor for impact loads =  $(0.25) * (95,880)$ .. -23,970 lbs  
 71,910 lbs
- 5) Maximum design tension..... 71,910 lbs

6) Implied design factor =  $159,800/71,910$ ..... 2.2

The guylines, in many cases, also run over sheaves. However, since the guylines are not moving, a reduction in the strength of the rope was not made because the guyline is not repeatedly bent over a sheave or drum. Since the guylines usually stabilize the tower, safety of the crew is a concern. Therefore, an increase in the design factor may be warranted to account for risk to personnel and property.

This type of rational could be extended to other cable yarding systems. For example, a standing skyline system may have a different design factor for the skyline and mainline since the skyline remains relatively static in comparison to the mainline. The mainline is pulled over sheaves and wound on to the drum at every carriage trip. Other factors to consider in this type of analysis might be the amount of abrasion a line could receive, wire rope maintenance, and rope construction.

## LINE LENGTH

Line length is not usually considered in the selection of design factors, but it could have an effect. Within the elastic range, wire rope can have significant stretch while storing energy. The amount of energy which can be stored before a wire rope reaches its elastic limit might be considered a cushion against impact loads.

Within the elastic range we can solve for the stretch,  $dL$ , by rearranging EQ. 1 and defining  $dTa$  as the change in tension which caused the change in length [13].

$$dL = \frac{dT_a * L}{A * E} \quad [\text{EQ. 10}]$$

Where:

- $dL$  = change in length of the wire rope (ft)
- $L$  = unstretched length of the wire rope (ft)
- $dTa$  = average tension change in the wire rope (lb)
- $A$  = metallic area of the wire rope (sq. in.)
- $E$  = modulus of elasticity of rope (psi)

As the initial line length,  $L$ , increases, so does the absolute amount of stretch,  $dL$ , required to bring the line up to some tension. Therefore, a long line will have significantly more absolute stretch than a short line when both lines have the same tension (Figure 5). EQ. 10 assumes "weightless" lines. Since lines have a catenary shape due to their weight, the actual stretch

will differ somewhat from the stretch predicted from EQ. 10 [7]. At high tensions, these differences are insignificant.

For example, a 3000-foot line subjected to a 40,000 pound tension, will have an absolute stretch 15 times more than the stretch of a 200-foot cable.

It will also take 15 times more work to stretch the longer line.

| <u>LINE LENGTH (ft)</u> | <u>STRETCH (ft)</u> |
|-------------------------|---------------------|
| 200                     | 1.13                |
| 500                     | 2.83                |
| 800                     | 4.52                |
| 1100                    | 6.22                |
| 1400                    | 7.91                |
| 1700                    | 9.61                |
| 2100                    | 11.86               |
| 2400                    | 13.56               |
| 2700                    | 15.25               |
| 3000                    | 16.95               |

**Figure 5. Stretch At Various Line Lengths. 40,000 lb Tension, 1-inch Rope.**

The significance of this in terms of design factors relates to dynamic loads occurring during yarding. If a dynamic load occurred, such as a hang-up, the operator has more time to respond with a longer line lengths than with a shorter length due to the greater amount of energy (work) the longer line requires to stretch. As an example:

Initial tension on mainline = 10,000 lb (before hang-up)

Final tension on mainline = 34,500 lb (elastic limit)

Wire rope diameter = 1-inch, metallic area = .470 sq inch

Initial line length = 2,000 ft

Modulus of elasticity = 12,000,000 psi

Power at drum = 50 hp, or 27,500 ft-lb/sec

Line stretch from tension in mainline (from EQ. 10) = 8.69 ft

If we assume that the maximum tension in the mainline during the hang-up occurs within the elastic region (linear region of Figure 2) of the wire rope, then the work required to change the tension from 10,000 lb to 34,500 lb is a function of the change in tension and change in length [2].

$$W = \frac{(dT_a * dL)}{2} \quad [EQ. 11]$$

Where:     W = work (ft-lb)  
          dT<sub>a</sub> = change in mainline tension (lb)  
          dL = change in length of wire rope due to dP  
              (ft)

Substituting into EQ. 11, we find the work performed is 106,427 ft-lb. Dividing the work by the rate at which the work could be done (power) yields approximately 4 seconds until the wire rope reaches its elastic limit. If the operator could react to the hang-up within 4 seconds, he could prevent the wire rope from reaching its elastic limit.

Other cable-using industries appear to use this concept. The mining industry varies its design factor as line lengths increase (Figure 6) [5].

As line length increases, the design factor decreases. This same principle may apply to cable logging systems. No rules have been established in the logging industry as to what constitutes a "long"

line length or how much the design factor could be reduced at long line lengths.

| <u>DEPTH</u> | <u>DESIGN FACTOR</u> |
|--------------|----------------------|
| to 500 ft    | 8.0                  |
| 500-1000 ft  | 7.0                  |
| 1000-2000 ft | 6.0                  |
| 2000-3000 ft | 5.0                  |
| 3000+ ft     | 4.0                  |

**Figure 6. Mining Industry Design Factors.** (Roebling Wire Rope Handbook, 1966)

## DESIGN FACTORS AND YARDING ECONOMICS

Historically, design factors in other industries have been devised to maximize the service life of the wire rope [13]. Maximizing service life may not maximize profit or minimize overall cost per unit volume. In cable yarding, log production is a very important factor. The logload which can be transported to the landing and the speed of the transport determine, to a large extent, the hourly production rate. In order to maximize production it may be necessary to operate at higher line tension and possibly a lower wire rope service life than that tension which would maximize line life. Although ropes used in such a manner must be replaced more often, work may be accomplished at a lower cost per unit volume because wire rope costs are relatively minor as compared to labor in logging operations in the western United States.

## PROPOSED METHOD FOR DESIGN FACTOR SELECTION

Assume an operator has the objective of minimizing his yarding cost. In order to do this for a given line size, some optimal production rate must exist. For a particular yarding machine and ground condition (profile, deflection, etc.), this production rate is directly related to the logload which can be yarded to the landing. The size of logload, yarder engine, drive train, and ground conditions affect the rate the logs can be delivered to the landing. The yarding cost per unit volume can be calculated by dividing the hourly yarding cost by the hourly production.

$$\frac{\text{Yarding Cost}}{\text{Unit Volume}} = \frac{\frac{\text{Yarding Cost}}{\text{HR}}}{\frac{\text{Volume Yarded}}{\text{HR}}} \quad [\text{EQ. 12}]$$

The life of the wire rope will vary as the logload varies because the tensions in the operating lines are almost linearly related to the logload transported to the landing. As the logload increases, line tensions increase, and the corresponding rope life decreases because of the larger bearing pressure ratio (EQ. 6 and Figure 4). Therefore, the yarding cost per hour in EQ. 12 will vary along with the line life (all other factors remaining constant).

A systematic procedure for calculating design factors based on yarding cost and line life is described in the following 12 steps. It is based upon the fatigue life of wire rope using the

relationships from Drucker and Tachau (EQ. 6 and Figure 4) [1]. The number of bends under various tensions are calculated using yarding simulation. The flow chart below (Chart 1) summarizes the procedure.

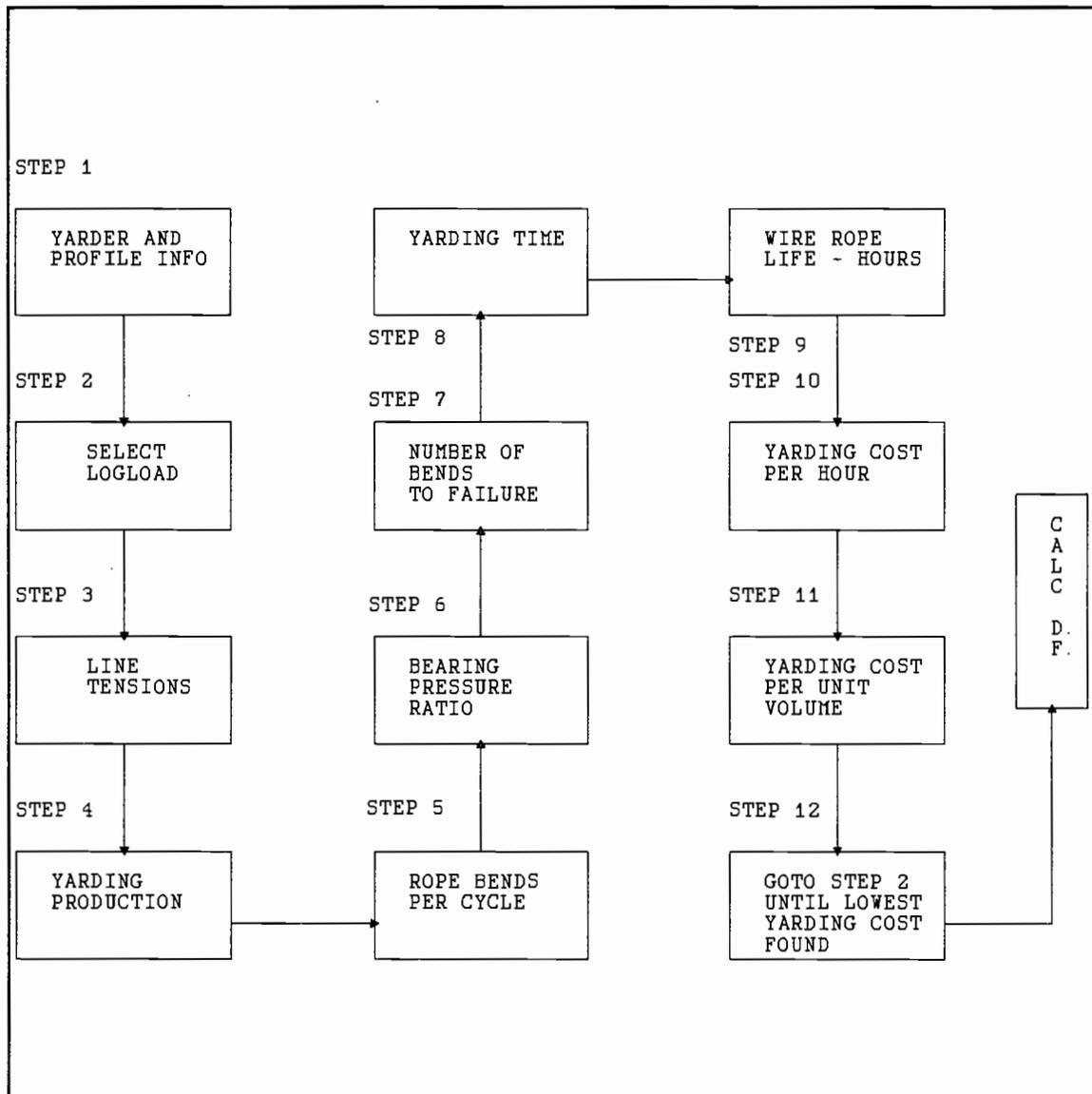


Chart 1. 12 Step Flow Chart.

- 1) Obtain yarder information for the desired cable logging configuration (running skyline, standing skyline, etc.).

This information should include estimates of sheave sizes, line diameters and lengths, and engine performance specifications. In addition, information on the overall geometry of the area to be yarded (the ground profile) is also necessary.

- 2) Start with a relatively low logload. From here, logloads can be increased or decreased in an iterative fashion to determine the optimal logload in terms of yarding cost per unit volume. For example, logloads ranging between 6,000 and 18,000 pounds could be examined in 2,000 pound increments.
- 3) Based on the logload determined above, the geometry of the area to be yarded, and line sizes, obtain the tensions in the operating lines at terrain points along the ground profile of the area to be yarded. The tension can be obtained in many ways:
  - a) skyline yarding software (LOGGER PC) [15]
  - b) graphical methods [16]
  - c) chain and board procedures [16]
  - d) experience
- 4) Based on the logloads and tension in the operating lines, find the production per yarding cycle and the production

per hour. As with determining the line tensions, production can be determined by experience or by simulation using yarder engine performance, drivetrain characteristics, and stand characteristics.

5) Determine the number of bends a given section of line makes under tension in one yarding cycle over the smallest sheave in the system. By using the smallest sheave, a worst case scenario will be represented (in terms of bends until failure as per Figure 4). For example, the haulback line on a running skyline may make 1 bend per turn over a 12-inch sheave (at maximum tension) at the tower. The same section of rope will also make 1 bend on the drum of the yarder at about the same tension (but a different diameter). Therefore 2 bends will be made by the haulback on a particular section of line for the yarding cycle.

6) Based on the sheave and drum diameters, line diameter, and tension in the line, calculate the bearing pressure

(B) ratio from EQ. 6 for each bend [1]:

$$B = \frac{(2 * T)}{(U * d * D)} \quad [\text{EQ. 6}]$$

Where U = the breaking strength of an individual wire for  
6 X 19 wire rope, psi

- 7) Use Figure 4 to approximate the number of bends to failure given "B" calculated above. This graph is only good for 6 X 19 wire rope. The relationship between bearing pressure ratio and bends to failure can be approximated by a hyperbolic relationship.

$$N = \left( \frac{1.1012}{B} \right)^{2.05} \quad [\text{EQ. 13}]$$

Where N = the approximate number of bends until failure

At each terrain point of the ground profile, tensions in the operating lines are calculated. Given a ground profile in which the yarding is uphill, the maximum tension will occur at the top of the headspar. Taking the bearing pressure ratio at this point, given the diameter of the wire rope and the diameter of the sheave, allows the number of bends to failure (N) to be calculated. The calculations are repeated at the drum. This same procedure is repeated for each terrain point as the turn is yarded in.

The "cumulative damage" equation (EQ. 8) is used to express the life of the rope used up at any given tension. The cumulative damage will sum to unity at failure [17].

$$\sum_{i=1}^k \frac{1}{N_i} = 1 \quad [\text{EQ. 8}]$$

Where:  $N_{i-k}$  = wire rope life (bends until failure) at varying tensions,  $i$  to  $k$ , until the wire rope fails (Figure 4)

EQ. 8 is used to determine the proportion of the line life used to yard a particular area or corridor. Since the fraction of line life used up (for a particular section of line) at each tension along the span of the yarding system during log inhaul is equal to the reciprocal of the corresponding line life [17], the amount of line life used for the corridor is obtained with EQ. 9. The largest proportion of line life used (at some terrain point) represents the shortest life (in terms of hours) for the line on the profile.

$$FL = \sum_{i=1}^n \frac{1}{N_i} \quad [EQ. 9]$$

Where:  $N_{i-n}$  = wire rope life (bends until failure) at varying tension (Figure 4),  $i$  to  $n$ , over the corridor or area to be yarded (provided failure has not occurred)

FL = proportion of the wire rope life used up to yard the corridor or area

- 8) Calculate the total number of hours to yard the profile (corridor) by dividing the total volume in the corridor

by the production rate.

$$\text{Total hours} = \frac{\text{Corridor volume}}{\frac{\text{Volume yarded}}{\text{Hour}}} \quad [\text{EQ. 14}]$$

- 9) Determine the approximate life (in hours) of the wire rope from the information from steps #6 and #7 by dividing the total hours to yard the corridor (step #8) by the proportion of line life used to yard the corridor. Do this for each line (mainline, haulback, etc).

$$\text{Rope life hours} = \frac{\text{Total hours}}{\text{Proportion of life used}} \quad [\text{EQ. 15}]$$

- 10) Determine the yarding cost per hour for the yarder selected in step #1. This cost should include an expense for the operating lines with an appropriate life determined from step #9. The line cost per hour is calculated by dividing the total cost to purchase the wire rope by the life of the rope. This line cost will vary with the line life as different logloads are examined (step #2). Therefore, the yarding cost per hour for the yarder will also vary (all other factors remaining constant). The hourly yarding cost can be calculated by:

- a) computer software such as PACE [4] or the U.S. Forest Service empirical appraisal software [10]
- b) various hand calculation methods

c) experience

- 11) Calculate the yarding cost per unit volume from EQ. 12 above.
- 12) Repeat steps #1 through #11 for increasing (or decreasing) logloads. Continue the process until you bracket the range of logloads which yield the lowest yarding cost per unit volume (Diagram 1).

Determine the implied economic design factor from the tension associated with the optimum logload found in step #12 for each line being investigated (EQ. 16).

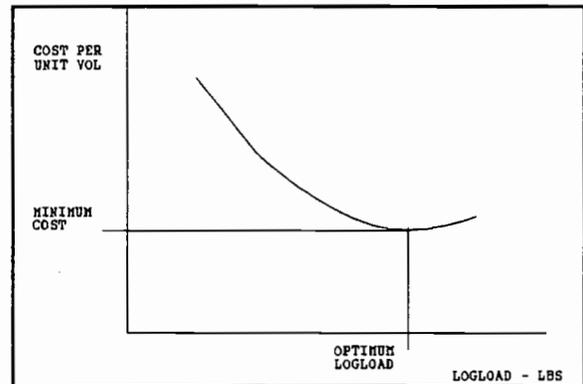


Diagram 1. Minimum Yarding Cost Determination.

$$D.F. = \frac{(\text{Breaking strength of rope})}{(\text{Tension of rope associated with payload})} \quad [\text{EQ. 16}]$$

Where D.F. = Design factor

## AN EXAMPLE USING SIMULATION

A logging engineer wants to determine the feasibility of skyline yarding an area. One of the first questions which must be answered is what the upper limit of tension the operating lines can have. Historically, the engineer would divide the breaking strength of the line by 3 (design factor = 3) to determine the maximum allowable tension. With this information, the engineer proceeds with payload analysis for various profiles in the planning area. The example which follows will demonstrate the use of economics for determining a design factor for logload analysis in the planning area.

The example uses the 12 steps presented previously. We will track through a hypothetical situation to determine the economic design factor. Assumptions on yarder specifics, stand details, and terrain profile are also displayed. A summary of the results are presented in several tables and graphs at the end of this section.

- 1) Yarder Specifics:
  - a) Running skyline configuration with mechanical interlock, 50-foot tower, 3500 feet of 7/8-inch haulback and 1750 feet of 7/8-inch mainline [16].
  - b) All sheaves have a 12-inch diameter.
  - c) Breaking strength of 7/8-inch rope (EIPS) is 79,000 lbs [13].

- 2) The timber stand consists of 80 trees per acre to be harvested. The logs are distributed randomly throughout the area, with diameters ranging from 10 to 40 inches. Maximum and minimum log lengths are 35 and 11 feet respectively with a taper of one inch for every eight feet of length. Log lengths must be in 2 foot increments (11, 13, 15, ..., 35 foot lengths).
  
- 3) Yarding simulation software was used to determine the logload, line tensions, production rates, and do the necessary calculations required for the determination of the design factor. Production rates are based on log load size, the terrain profile, and line speed capabilities of the yarder. An effective hour of 45 minutes was utilized in order to account for delays in the yarding cycle. A hypothetical engine torque curve and drive train was used. Uphill yarding was simulated on the profile. The tailspar was set at 5 feet. The maximum yarding distance was 1,400 feet. Average logloads were generated by setting a maximum logload and averaging the weight of the logs yarded each turn. A more complete description of the yarding simulation software is included in the appendix. The ground profile is assumed to be representative of the entire area to be yarded. In this example, only one profile is used. However, several profiles could just as easily been

utilized and the results averaged. Full log suspension was required at all terrain points.

- 4) Yarding equipment costs per hour were developed on the PACE software (Sessions 1985) [4]. Delivered cost of the yarder was assumed to be \$500,000. The life of the yarder was assumed to be 8 years regardless of power requirements [10]. Operating time per day was presumed to be 8 hours. The equipment cost includes operating costs, ownership costs, and labor costs. Ownership costs includes annual interest expense, taxes, license, insurance, and storage. Labor consisted of a 5 person crew with a 2 hour travel time per day and an overhead cost of 5% of the direct labor cost. The operating cost included maintenance, repairs, fuel, and lube. Wire rope costs were included in the operating cost using a rope life estimated from Figure 4 (and converted to hours) for each trial maximum logload. The total yarding cost (\$/hour) was generated for each logload as per step #11 above.

The line life is the variable factor in determining the equipment cost per hour (all other factors remaining constant). Since for each logload simulated a different line life is obtained, the hourly line cost will vary. Therefore, the equipment cost per hour will vary with

line life.

- 5) The equipment cost data generated by PACE (minus the line costs) was incorporated into the yarding simulation model in order to produce the final output (Tables 1,2, and 3). See the appendix for examples of PACE calculations and output.

## RESULTS

As suggested in step #2, the simulation was done for 7 maximum logloads (6,000, 8,000, 10,000, 12,000, 14,000, 16,000, and 18,000 lbs). The maximum logloads were chosen in order to generate a range of reasonable line tensions. The yarding simulation program preformed the calculations outlined in the 12 step procedure presented earlier. The appendix provides a more detailed listing of the yarding simulation output.

Simulation results indicated a trend of increasing yarding production (per hour) as logloads increased. However, this trend was only true up to the point where the production increase from larger logloads was more than offset by the decrease in production from corresponding longer cycle times (Table 1). Wire rope life (hours) decreased with increasing logloads (Table 2). Cost per unit volume yarded was calculated using the production per hour and the equipment cost per hour for each logload in step #11 (Table 2).

Table 1 offers a comparison of the 7 logloads in terms of mainline tension, haulback tension, volume yarded per turn, and volume yarded per hour. Note the increasing production rates as logload is increased. At the largest logload, the production decreases. This decrease is due to the increased cycle and hook time associated with the large logload. The production decrease due to longer cycle times more than offsets the production increase form

larger payloads. Haulback and mainline tensions increase as logloads are increased.

Table 2 displays wire rope life for both the haulback and mainline and corresponding per hour and per unit volume equipment costs. The line life decreases as logloads (and thus line tensions) increase. As the logload increased to approximately 13,130 pounds, yarding cost per unit volume decreased because the production per hour increased even though equipment cost and wire rope cost per hour increased (Figure 7). Logloads greater than 13,130 pounds increased yarding cost per unit volume because of the increase in wire rope cost per hour. At the largest logload (15,876 lbs), the production per hour decreased which also contributed to the increased equipment cost per unit volume.

| <u>MAXIMUM LOGLOAD</u> | <u>AVERAGE LOGLOAD</u> | <u>MAXIMUM ML TENS</u> | <u>MAXIMUM HB TENS</u> | <u>MBF/TURN</u> | <u>MBF/HR</u> |
|------------------------|------------------------|------------------------|------------------------|-----------------|---------------|
| 6,000                  | 5,650                  | 20,081                 | 17,701                 | 0.71            | 6.40          |
| 8,000                  | 7,559                  | 24,711                 | 21,701                 | 0.94            | 7.51          |
| 10,000                 | 9,491                  | 29,050                 | 25,451                 | 1.19            | 8.50          |
| 12,000                 | 11,340                 | 33,677                 | 29,451                 | 1.42            | 9.04          |
| 14,000                 | 13,131                 | 38,302                 | 33,451                 | 1.64            | 9.42          |
| 16,000                 | 14,675                 | 42,928                 | 37,451                 | 1.83            | 9.59          |
| 18,000                 | 15,876                 | 47,553                 | 41,451                 | 1.98            | 8.80          |

**Table 1. Values Produced By Yarding Simulation, Running Skyline System.**

From Table 2 and Figure 7, the logload which results in the lowest

equipment cost per unit volume (\$22.73) is approximately 13,130 pounds. At this logload the rope lives of the haulback and mainline are short (437 and 337 hours respectively). However, the increased rope cost is more than offset by the higher production rates.

| AVERAGE<br>LOGLOAD | ROPE LIFE (HR) |       | EQUIP COST/HR | EQUIP COST/MBF |
|--------------------|----------------|-------|---------------|----------------|
|                    | HBK            | MLN   |               |                |
|                    | 5,650          | 1,002 |               |                |
| 7,559              | 734            | 572   | 197.83        | 26.33          |
| 9,491              | 596            | 462   | 203.32        | 23.92          |
| 11,340             | 501            | 387   | 208.88        | 23.10          |
| 13,131             | 437            | 337   | 213.99        | 22.73          |
| 14,675             | 394            | 303   | 218.29        | 22.75          |
| 15,876             | 404            | 310   | 217.27        | 24.70          |

Haulback = 2 bends/turn, Mainline = 2 bends/turn

**Table 2. Rope Life & Equipment Costs, Running Skyline System.**

| LOGLOAD | HB DESIGN FACTOR | ML DESIGN FACTOR |
|---------|------------------|------------------|
| 5,650   | Approx 4.5       | Approx 4.0       |
| 7,559   | Approx 3.7       | Approx 3.2       |
| 9,491   | Approx 3.1       | Approx 2.7       |
| 11,340  | Approx 2.7       | Approx 2.4       |
| 13,131  | Approx 2.4       | Approx 2.1       |
| 14,675  | Approx 2.1       | Approx 1.9       |
| 15,876  | Approx 1.9       | Approx 1.7       |

Design factors = (breaking strength) / (max tension)

**Table 3. Implied Economic Design Factors, Running Skyline System.**

Design factors were calculated for each of the 7 logloads using EQ. 16. Table 3 displays the results of these calculations. The maximum tension for each logload generated by simulation was used as the denominator in EQ. 16 (Table 1). Figure 8 displays a graphical representation of the design factors.

It is possible that the optimum logload could result in an implied economic design factor near the elastic limit of the wire rope. In our example, a logload of 15,876 pounds produces a maximum tension of 47,451 pounds in the mainline. The resulting design factor (1.7) is near the elastic limit of this size wire rope. Recall from the previous discussion on the elastic limit that for ropes

used in logging, the elastic limit is 60% to 65% of the breaking strength of the rope (a design factor of 1.67 to 1.54). Tensions above the elastic limit can result in a permanent reduction in the overall tensile strength of the rope. For this reason, logloads which result in tensions greater than the elastic limit should not be considered feasible.

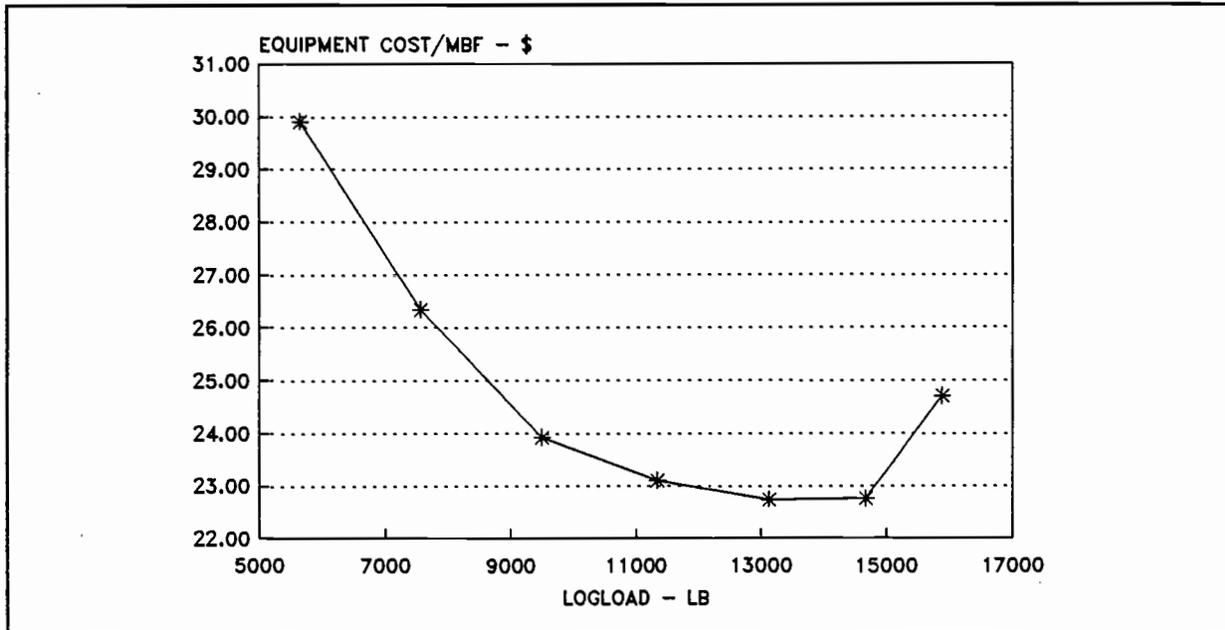


Figure 7. Equipment Costs At Various Payloads, Running Skyline System.

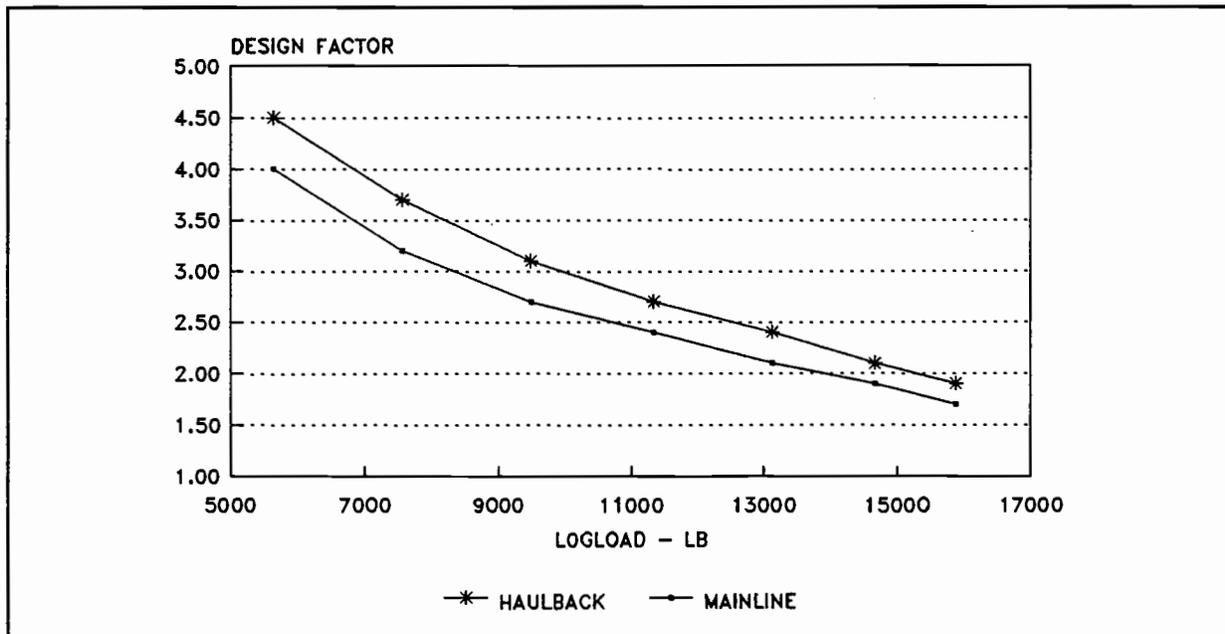


Figure 8. Implied Economic Design Factors, Running Skyline System.

This example demonstrates how yarding costs can be used for calculating design factors. The method demonstrated here can be applied in almost any situation given the proper information. Different yarding systems, stand situations, and specific ground conditions may generate different results and therefore differing design factors. The effect of dynamic loads on the calculation of design factors was not considered.

Crew safety was not incorporated into the procedure. One way to include safety as a consideration would be to reduce the lives of the operating lines determined by the simulation program (for example, take 80% of the calculated hourly line life).

**ALTERNATE PROCEDURE**

If yarding simulation is not available, line lives can be estimated using average tensions and average drum diameters. This procedure is less reliable since EQ. 6 and EQ. 8 are non-linear relationships. Rope life can be calculated by first determining the bends per hour the line makes (EQ. 17).

$$\frac{\text{Bends}}{\text{HR}} = \left( \frac{\text{Cycles}}{\text{HR}} \right) * \left( \frac{\text{Bends}}{\text{Cycle}} \right) \quad \text{EQ. 17}$$

Information on the number of bends per cycle and cycles per hour were obtained in steps #4 and #5. The number of bends until failure are calculated by EQ. 13. The wire rope life (in hours) can then be calculated from EQ. 18.

$$\text{Rope life hours} = \frac{\text{Bends until failure}}{\frac{\text{Bends}}{\text{HR}}} \quad \text{EQ. 18}$$

The yarding cost per unit volume can then be determined, as it was for yarding simulation, from EQ. 12. A comparison of the two methods are displayed in Table 4.

| <u>AVG<br/>LOGLOAD</u> | <u>COST/HR<br/>SIMULATION</u> | <u>COST/HR<br/>AVERAGES</u> |
|------------------------|-------------------------------|-----------------------------|
| 5,650                  | 29.90                         | 29.56                       |
| 7,559                  | 26.33                         | 26.24                       |
| 9,491                  | 23.92                         | 24.08                       |
| 11,340                 | 23.10                         | 23.12                       |
| 13,131                 | 22.73                         | 22.90                       |
| 14,675                 | 22.75                         | 23.01                       |
| 15,876                 | 24.70                         | 25.41                       |

**Table 4. Comparison - Simulation VS Averages, Running Skyline System.**

## DISCUSSION AND CONCLUSIONS

The objective of this paper was to 1) review factors which affect wire rope life and 2) propose a method for choosing a design factor which incorporates yarding costs. At the current time, little documentation exists on this topic. Indeed, no hard and fast rule for design factors can be applied to cable yarding installations unless one considers the convention of using a design factor of 3.0 as the absolute policy. It seems apparent however, that a starting point for such a rule must start at recognizing the elastic limit of the wire rope (60% - 65% of the breaking strength) [5]. When this limit is exceeded, the efficiency of the rope is greatly impaired and the rope life seriously reduced. Beyond this point the situation gets more complex.

Several factors involved in determining design factors were introduced in this paper. The first, line type or use, suggested that it may not be appropriate to use the same design factor for all lines used in a cable yarding operation. Lines which are constantly moving over sheaves, under high tensions, or subject to abrasion should have higher design factors than lines which are static or do not move since the lives of moving lines will probably have shorter lives. For example, it is entirely possible that a mainline or haulback line may warrant a higher design factor than a guyline. However, due to the cost of failure, the choice of a

design factor for guylines should take safety into consideration.

The second approach dealt with the length of the wire rope in use. At longer lengths, wire ropes operated in the elastic region are capable of storing a significant amount of energy. In terms of impact loads or hang-ups, this ability to store energy (stretch) may be important to provide reaction time for an operator to prevent a tension above the elastic limit. For example, if a sudden hang-up is encountered on a relatively long span, due to the line stretch the operator may be able to reduce the tension before excessive tensions are reached. On a shorter span this may not be possible due to the small amount of energy required to stretch the line to its elastic limit. Therefore, it is possible that lower design factors are appropriate for long wire rope spans.

The final approach examined in this paper explored the influence of yarding costs in calculating design factors. A systematic approach was presented with the objective of minimizing equipment yarding costs. The procedure introduced in this paper illustrated a rational approach to the question of design factors in cable yarding considering line life as affected by bends under tension. The 12 steps presented a method of calculating design factors based on the economics of skyline yarding. Yarding simulation was introduced as an effective technique of incorporating the 12 step method.

To the supervisor of a cable yarding operation, this strategy may be more reasonable than applying a factor of 3.0 in all cases. The economics of cable yarding is often determined by the production rate at which logs can be delivered to the landing. To maximize this production rate, it is often necessary to operate at high line tensions. Knowing the range of tensions which will produce logloads that are optimal and thus minimize yarding cost may be important.

To the logging engineer or planner, economic design factors provide a starting point for logload analysis and equipment selection. If a logging engineer wants to determine the feasibility of skyline yarding an area, one of the first questions which must be answered is what the upper limit of tension the operating lines could be subjected to. Historically, the engineer would divide the breaking strength of the line by 3 (design factor = 3) to determine the maximum allowable tension. Using design factors based on the yarding cost is a more rational approach and may result in more efficient planning over the long term. With this information, the engineer can proceed with logload analysis, road and landing location, and equipment selection in the planning area.

## RECOMMENDATIONS

This paper serves as an introduction to design factors in cable yarding. Much more work needs to be done in this field.

Additional research is needed to:

- 1) Examine the relationship between line lengths and energy storage in choosing design factors. Although this topic was touched on in this paper, it is apparent more work is needed. Indeed, the whole question of dynamic loads in cable yarding is a poorly understood and was not considered in this paper. Is line life increased because the operator, in some cases, can react to sudden hang-ups to prevent excessive tension before the elastic limit is reached?
  
- 2) Look at the size of sheaves used in cable yarding. It is impractical to design very large tail blocks due to the difficulty of transport and rigging of these blocks in remote areas. However, the possibility exists that sheaves on yarder tower could be redesigned with the efficiency of wire rope as a major factor [3].  
Currently, most tower sheaves are relatively small (12 to 14 inch) and severely affect the life of a wire rope. This is particularly true for operating lines such as mainlines and haulback lines. As shown in this paper,

sheave size increases can significantly increase wire rope life as per the bearing pressure ratio and bends to failure graph (Figure 4) [3].

- 3) Several line types, specifically Dyform [8] and P.F.V [9] (plastic filled valley) type rope, are available which show increased line life, tensile strength, and resistance to bending fatigue and abrasion. These ropes are used widely in the western United States for logging applications. Preliminary results indicate that yarding costs (on US Forest Service appraised timber sales) can be reduced by using these lines [14]. How should design factors be calculated for these ropes?

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## APPENDIX A

### YARDING SIMULATION

Yarding simulation was used to calculate the parameters used in this paper. This program was originally developed by the author as a part of a graduate course in logging mechanics at Oregon State University [11]. Line life computations were added to the program for this project. Line tensions are based on rigid-link assumptions.

Information about the timber stand, yarding equipment, and the topography of the terrain is used to determine yarding production, line tensions, yarding costs, and wire rope life. Costs such as felling and bucking, loading, and hauling are not included in the simulation. The program was written in BASIC and a program listing is attached. In addition, a general flow chart of the program is also included in Appendix A (Chart 2).

The simulation models a running skyline system (Diagram 2). The main components are as follows.

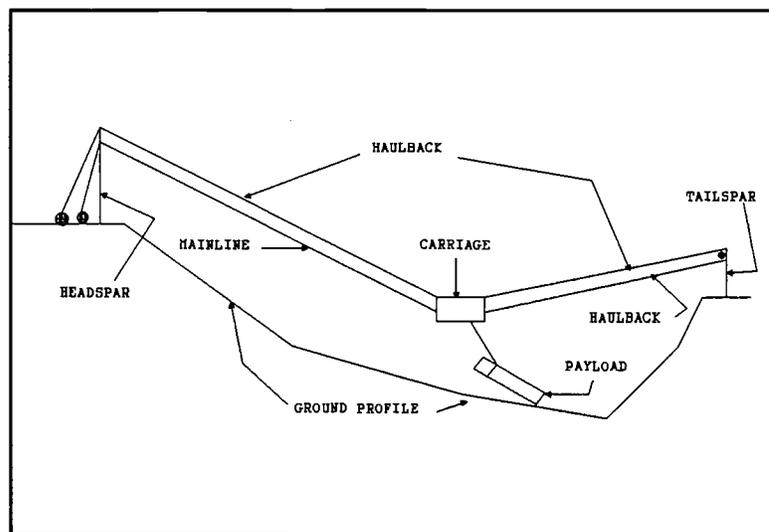


Diagram 2. Running Skyline System.

- 1) Timber Stand Generation - Logs to be yarded are created from tree sizes specified by the user. Eighty (80) cut tree per acre are used for this simulation. The trees are "felled" and "bucked" into specific lengths. In this case, logs can be from 11 feet to 35 feet in length. Intermediate lengths are in 2-foot increments (13,15,17,...33). Large end diameters range from 10 to 40 inches. The maximum weight an individual log can have is also be specified. The program will attempt to cut the longest log length possible within the constraints of maximum weight and length of tree remaining. The minimum small end diameter is 8 inches. The taper is set at 1 inch in 8 feet. The logs are distributed randomly throughout the yarding corridor specified by some maximum lateral yarding distance. Log weights are based on a pounds per cubic foot basis (40 pounds = 1 cubic foot). The logs are sorted and positions identified by X,Y coordinates.
  
- 2) Log Hook - Chokers are filled by logs until all chokers are full or the maximum logload is reached, whichever occurs first. The range of maximum logloads used are 6,000, 8,000, 10,000, 12,000, 14,000, 16,000, and 18,000 pounds. Chokers are attached by either rings or sliders. Hook times are accumulated for each turn along with outhaul times.
  
- 3) Line Tensions - The line tensions at a given terrain

point are determined iteratively by estimating an initial haulback tension, calculating the various resulting line tensions, calculating the resulting logload, and comparing the resulting logload with the actual logload. The carriage clearance is set at 40 feet (full log suspension). If the calculated logload is within some tolerance of the actual (100 lbs), parameters are recorded for the turn at the terrain point. The program then moves to the next terrain point and repeats the process. If the difference between actual and calculated logloads is more than the allowed tolerance, a new haulback tension is used and new logload calculated until the tolerance is less than the minimum.

- 4) Line Speeds and Inhaul Time - Once the correct line tensions are determined for each terrain point on a given turn, the inhaul time can be calculated. The program computes the effective drum radius and speed of the mainline drum based on the tension in the mainline, converter torque, and required engine torque. Given the mainline drum speed, the inhaul time from terrain point to terrain point can be computed and accumulated for each turn.
- 5) Line Life - At each terrain point tensions in the operating lines are calculated. Given the profile used in the simulation, the maximum tension will occur at the top of the headspar. Taking the bearing pressure ratio

at this point, given the diameter of the wire rope and the diameter of the sheave, allows the number of bends to failure to be calculated. The same calculations are performed at the drum and the two results summed. This same procedure is repeated for each terrain point as the turn is yarded in. If all turns are accumulated at each terrain point and the reciprocal taken, the proportion of the line life used to yard the corridor is obtained (as per EQ. 8) [17]. The following equations are used to compute line life (in terms of hours) in the yarding simulation program:

$$LIFE_{hr} = \sum \left( \frac{HOURS}{PROPORTION} \right)$$

$$LIFE_{bends} = n * \sum \left( \frac{TURNS}{PROPORTION} \right)$$

Where:     n = the number of bends per turn  
               Sum Turns = total number of turns  
               Sum Hours = total hours to yard corridor

- 6) Cost Computations - Equipment costs are calculated by the simulation program in a similar manner to the techniques presented in the body of the paper (13 steps).
- 7) Design Factors - Design factors for each maximum logload are calculated as per EQ. 16 in the body of the report.
- 8) Print Results - The results are printed on the screen or sent to the printer. The output of the yarding

simulation program for the 7 logloads used in this paper are included in this appendix.

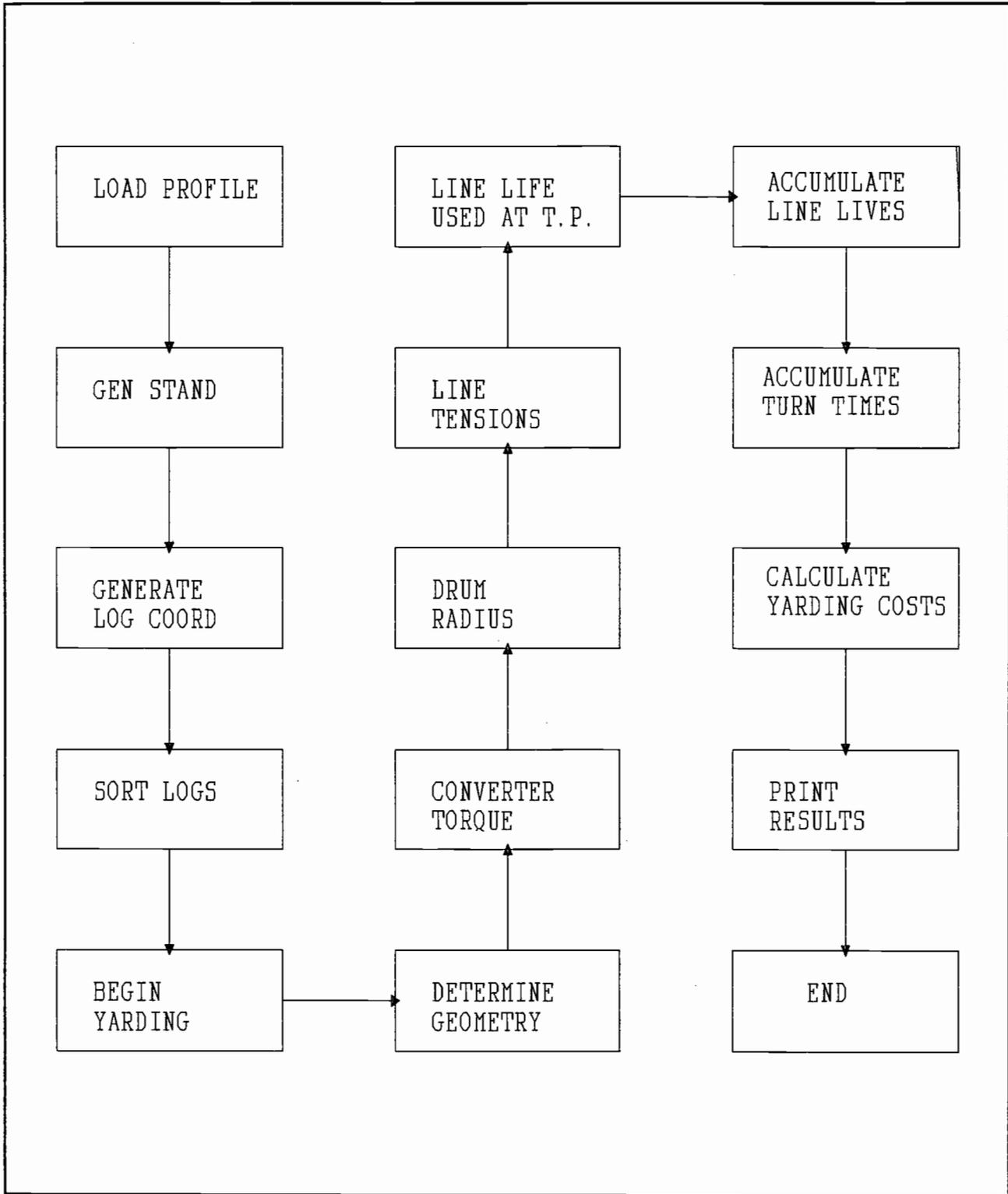


Chart 2. Yarding Simulation Flow Chart.

SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 6,000

TOTAL TURNS YARDED = 309

TOTAL LOGS YARDED = 636

AVE LOGS PER TURN = 2.1

URNS/HR = 9.1

AVE PAYLOAD (LBS) = 5,650

AVE VOLUME/TURN (MBF) = 0.71

VOLUME YARDED/HOUR (MBF) = 6.40

MAX ML TENSION = 20,081

MAX HB TENSION = 17,701

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 18,175

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 14,278

HAULBACK LIFE (HRS) = 1,002

MAINLINE LIFE (HRS) = 787

EQUIPMENT COST PER HOUR = \$191.50

EQUIPMENT COST PER UNIT VOLUME = \$29.90

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$29.56

DESIGN FACTOR FOR HAULBACK = 4.49

DESIGN FACTOR FOR MAINLINE = 3.96

Simulation Output - Maximum Logload = 6,000 lbs

SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 8,000

TOTAL TURNS YARDED = 231

TOTAL LOGS YARDED = 613

AVE LOGS PER TURN = 2.7

URNS/HR = 8.0

AVE PAYLOAD (LBS) = 7,559

AVE VOLUME/TURN (MBF) = 0.94

VOLUME YARDED/HOUR (MBF) = 7.51

MAX ML TENSION = 24,711

MAX HB TENSION = 21,701

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 11,673

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 9,099

HAULBACK LIFE (HRS) = 734

MAINLINE LIFE (HRS) = 572

EQUIPMENT COST PER HOUR = \$197.83

EQUIPMENT COST PER UNIT VOLUME = \$26.33

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$26.24

DESIGN FACTOR FOR HAULBACK = 3.66

DESIGN FACTOR FOR MAINLINE = 3.22

Simulation Output - Maximum Logload = 8,000 lbs

## SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 10,000

TOTAL TURNS YARDED = 184

TOTAL LOGS YARDED = 609

AVE LOGS PER TURN = 3.3

TURNS/HR = 7.2

AVE PAYLOAD (LBS) = 9,491

AVE VOLUME/TURN (MBF) = 1.19

VOLUME YARDED/HOUR (MBF) = 8.50

MAX ML TENSION = 29,050

MAX HB TENSION = 25,451

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 8,544

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 6,624

HAULBACK LIFE (HRS) = 596

MAINLINE LIFE (HRS) = 462

EQUIPMENT COST PER HOUR = \$203.32

EQUIPMENT COST PER UNIT VOLUME = \$23.92

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$24.08

DESIGN FACTOR FOR HAULBACK = 3.12

DESIGN FACTOR FOR MAINLINE = 2.74

**Simulation Output - Maximum Logload = 10,000 lbs**

## SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 12,000

TOTAL TURNS YARDED = 154

TOTAL LOGS YARDED = 607

AVE LOGS PER TURN = 3.9

URNS/HR = 6.4

AVE PAYLOAD (LBS) = 11,340

AVE VOLUME/TURN (MBF) = 1.42

VOLUME YARDED/HOUR (MBF) = 9.04

MAX ML TENSION = 33,677

MAX HB TENSION = 29,451

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 6,392

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 4,937

HAULBACK LIFE (HRS) = 501

MAINLINE LIFE (HRS) = 387

EQUIPMENT COST PER HOUR = \$208.88

EQUIPMENT COST PER UNIT VOLUME = \$23.10

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$23.12

DESIGN FACTOR FOR HAULBACK = 2.70

DESIGN FACTOR FOR MAINLINE = 2.36

**Simulation Output - Maximum Logload = 12,000 lbs**

## SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 14,000

TOTAL TURNS YARDED = 133

TOTAL LOGS YARDED = 607

AVE LOGS PER TURN = 4.6

URNS/HR = 5.7

AVE PAYLOAD (LBS) = 13,131

AVE VOLUME/TURN (MBF) = 1.64

VOLUME YARDED/HOUR (MBF) = 9.42

MAX ML TENSION = 38,302

MAX HB TENSION = 33,451

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 5,012

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 3,861

HAULBACK LIFE (HRS) = 437

MAINLINE LIFE (HRS) = 337

EQUIPMENT COST PER HOUR = \$213.99

EQUIPMENT COST PER UNIT VOLUME = \$22.73

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$22.90

DESIGN FACTOR FOR HAULBACK = 2.38

DESIGN FACTOR FOR MAINLINE = 2.08

**Simulation Output - Maximum Logload = 14,000 lbs**

## SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 16,000

TOTAL TURNS YARDED = 116

TOTAL LOGS YARDED = 607

AVE LOGS PER TURN = 5.1

URNS/HR = 5.2

AVE PAYLOAD (LBS) = 14,675

AVE VOLUME/TURN (MBF) = 1.83

VOLUME YARDED/HOUR (MBF) = 9.59

MAX ML TENSION = 42,928

MAX HB TENSION = 37,451

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 4,125

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 3,172

HAULBACK LIFE (HRS) = 394

MAINLINE LIFE (HRS) = 303

EQUIPMENT COST PER HOUR = \$218.29

EQUIPMENT COST PER UNIT VOLUME = \$22.75

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$23.01

DESIGN FACTOR FOR HAULBACK = 2.12

DESIGN FACTOR FOR MAINLINE = 1.85

**Simulation Output - Maximum Logload = 16,000 lbs**

## SIMULATION RESULTS

MAXIMUM PAYLOAD (LBS) = 18,000

TOTAL TURNS YARDED = 110

TOTAL LOGS YARDED = 607

AVE LOGS PER TURN = 5.5

URNS/HR = 4.4

AVE PAYLOAD (LBS) = 15,876

AVE VOLUME/TURN (MBF) = 1.98

VOLUME YARDED/HOUR (MBF) = 8.80

MAX ML TENSION = 47,553

MAX HB TENSION = 41,451

HAULBACK ROPE LIFE (NUMBER OF BENDS) = 3,581

MAINLINE ROPE LIFE (NUMBER OF BENDS) = 2,749

HAULBACK LIFE (HRS) = 404

MAINLINE LIFE (HRS) = 310

EQUIPMENT COST PER HOUR = \$217.27

EQUIPMENT COST PER UNIT VOLUME = \$24.70

EQUIPMENT COST PER UNIT VOLUME (AVERAGE) = \$25.41

DESIGN FACTOR FOR HAULBACK = 1.92

DESIGN FACTOR FOR MAINLINE = 1.67

**Simulation Output - Maximum Logload = 18,000 lbs**

```

/      ** RUNNING SKYLINE PROGRAM - FULL SUSPENSION - RIGID
LINK **
/      ** YARDING SIMULATION WITH LINE LIFE CALCULATIONS
**
/
CLS
COLOR 14, 1
CLS
/
/      ** INPUT GIVEN VARIABLES **
/
WA = 1.42: WMS = 1.42: CW = 1000: WH4 = WA
MHB = 0: HBTOT = 3500: MLTOT = 1750
DIM WMAX(100), DB(1000), DS(1000), NHB2(1000), NML2(1000)
DIM L(1000), W(1000), XX(1000), YY(1000)
DIM S(100), A(100), X(100), Y(100), PX(1000), DONE(1000),
CU(1000)
MLMAX = 0: HBMAX = 0
BENDTRHB = 1: BENDTRML = 1
/
/      ** RETREIVE PROFILE DATA FILE **
/
F$ = "MASTER.PRO"
OPEN F$ FOR INPUT AS #1
N = 0
INPUT #1, X(0), Y(0)
FOR I = 1 TO 100
    INPUT #1, S(I), A(I)
    A = ATN(A(I) / 100)
    X(I) = X(I - 1) + (S(I) * COS(A))
    Y(I) = Y(I - 1) + (S(I) * SIN(A))
    N = N + 1
    IF EOF(1) THEN GOTO NEXTONE
NEXT I
/
NEXTONE:
/
CLOSE #1
PRINT
S(0) = 0: A(0) = 0
PRINT "                                SIMULATION RUN"
/
/      ** INPUT HEADSPAR/TAILSPAR HEIGHTS & LOCATIONS **
/
PRINT : PRINT
INPUT "MAXIMUM PAYLOAD (LBS)"; MPAY
HS1 = 50: TP1 = 0
HS2 = 5: TP2 = 13
PRINT

```

```

/
/   ** GENERATE STAND **
/
PRINT : PRINT "*** CUTTING STAND ***"
START = TIMER
TPA = 80: K = 0: TAPER = 1 / 8
NTREE = INT(X(TP2 - 1) * 75 / 43560! * TPA)
FOR I = 1 TO NTREE
    DIAM = 10 + 30 * RND
    K = K + 1
/   DB(K) = DIAM
    GOTO SMEND
/
COUNT:
/
    K = K + 1
    DB(K) = DS(K - 1)
/
SMEND:
/
    DS(K) = DB(K) - 35 * TAPER
    L(K) = 35
/
LOGWT:
/
    W(K) = .00545 * (DB(K) ^ 2 + DS(K) ^ 2) * L(K) * 40 / 2
    IF W(K) < MPAY THEN GOTO TOPD:
    L(K) = L(K) - 2: DS(K) = DB(K) - TAPER * L(K): GOTO
LOGWT
/
TOPD:
/
    IF DS(K) > 8 THEN GOTO COUNT
    DS(K) = 8
    L(K) = INT((DB(K) - DS(K)) / TAPER)
    IF L(K) MOD 2 = 0 THEN L(K) = L(K) - 1
    IF L(K) < 11 THEN K = K - 1: GOTO NEXTI
    W(K) = .00545 * (DB(K) ^ 2 + DS(K) ^ 2) * L(K) * 40 / 2
/
NEXTI:
/
NEXT I
NLOG = K
FOR I = 1 TO NLOG
    CU(I) = .00545 * (DB(I) ^ 2 + DS(I) ^ 2) * L(I) / 2
NEXT I
/

```

```

'   ** GENERATE LOG COORDINATES **
'
FOR I = 1 TO NLOG
  XX(I) = INT(X(TP2 - 1) * RND)
  YY(I) = INT(75 * RND)
NEXT I
'
'   ** SORT LOGS BY OUTHAUL DISTANCE - SHELL SORT **
'
PRINT "*** START SORTING ***"
H = 1
'
RAP:
'
H = 3 * H + 1: IF H <= NLOG THEN GOTO RAP
'
HH:
'
H = H \ 3
FOR I = H + 1 TO NLOG
  V = XX(I): V1 = YY(I): V2 = W(I): V3 = DB(I): V4 =
DS(I): V5 = L(I): V6 = CU(I)
  J = I
'
NRAP1:
'
  IF XX(J - H) <= V THEN GOTO NRAP
  XX(J) = XX(J - H): YY(J) = YY(J - H): W(J) = W(J - H):
DB(J) = DB(J - H)
  DS(J) = DS(J - H): L(J) = L(J - H): CU(J) = CU(J - H)
  J = J - H
  IF J <= H THEN GOTO NRAP
  GOTO NRAP1
'
NRAP:
'
  XX(J) = V: YY(J) = V1: W(J) = V2: DB(J) = V3: DS(J) =
V4: L(J) = V5: CU(J) = V6
NEXT I
IF H <> 1 THEN GOTO HH
'
'   ** ASSIGN TERRAIN POINT POSITION FOR EACH LOG **
'
PRINT "*** IDENTIFYING LOG POSITIONS ***"
FOR I = 1 TO NLOG
  FOR J = NO TO N

```

```

                IF XX(I) > X(J) AND XX(I) < X(J + 1) THEN PX(I) = J:
NO = J: GOTO NI
        NEXT J
    ,
NI:
    ,
NEXT I
    ,
FOR I = 0 TO TP2 - 1
        WMAX(I) = MPAY
NEXT I
    ,
    ,   ** BEGIN YARDING UNIT **
    ,
PRINT   "** YARDING CORRIDOR **"
PRINT
FORM1$ = "   X-COORD   # LOGS   PAYLOAD   ML-MAX   HB-MAX
VOLUME"
FORM2$ = "   -----   -----   -----   -----   -----
-----"
PRINT FORM1$
PRINT FORM2$
ITT = 0
FOR K = 1 TO NLOG
    IF DONE(K) = 1 THEN GOTO NK
    X = XX(K) + 5
    Y = YY(K) + 5
    LOGS = 1
    WLOAD = W(K)
    VOL = CU(K)
    DONE(K) = 1
    FOR J = K + 1 TO K + 20
        IF J > NLOG THEN GOTO QUITER
        IF DONE(J) = 1 THEN GOTO NJ
        R = SQR((XX(J) - X) ^ 2 + (YY(J) - Y) ^ 2)      ' IF
    USING RING
        R = ABS(XX(J) - X)                            ' IF
    USING SLIDERS
        REACH = 25 - 3.1416 * DS(J) / 12
        IF R > REACH THEN GOTO NJ
        IF WLOAD + W(J) > WMAX(PX(K)) THEN GOTO NJ
        LOGS = LOGS + 1
        WLOAD = WLOAD + W(J)
        VOL = VOL + CU(J)
        DONE(J) = 1
        IF LOGS = 6 THEN GOTO QUITER
    ,
NJ:
    ,

```

```

NEXT J
,
QUITER:
,
GOSUB CALC
TURNS = TURNS + 1
SUMLOGS = SUMLOGS + LOGS
SUMVOL = SUMVOL + VOL
TIME1 = TIME1 + (1 * LOGS) + (.04 * Y)
TM2 = SQR(X ^ 2 + (Y(TP1) + HS1 - YYY - CL) ^ 2)
TIME2 = TIME2 + (TM2 / 800)
,
NK:
,
NEXT K
FOR I = TP1 TO TP2
    IF NML2(I) > LIFEML THEN LIFEML = NML2(I)
    IF NHB2(I) > LIFEHB THEN LIFEHB = NHB2(I)
NEXT I
IF NML1 > LIFEML THEN LIFEML = NML1
IF NHB1 > LIFEHB THEN LIFEHB = NHB1
TIME = INHAUL1 + INHAUL2 + INHAUL3 + INHAUL4 + TIME1 + TIME2
,
CLS
LOCATE 1, 7
PRINT CHR$(201); : PRINT STRING$(70, 205); : PRINT CHR$(187)
FOR I = 1 TO 22
    LOCATE I + 1, 7: PRINT CHR$(186): LOCATE CSRLIN - 1,
78: PRINT CHR$(186)
NEXT I
LOCATE 23, 7
PRINT CHR$(200); : PRINT STRING$(70, 205); : PRINT CHR$(188)
LOCATE 2, 35
PRINT "SIMULATION RESULTS"
LOCATE 4, 12
PRINT "TOTAL TURNS YARDED = "; TURNS
LOCATE 5, 12
PRINT "TOTAL LOGS YARDED = "; SUMLOGS
LOCATE 6, 12
PRINT USING "AVE LOGS PER TURN = #.#"; SUMLOGS / TURNS
,
BENDH = TURNS / (TIME / 45)
,
LOCATE 7, 12
PRINT USING "TURNS/HR = ##.#"; BENDH
LOCATE 8, 12

```

```

PRINT USING "AVE PAYLOAD (LBS) = ###,###"; PAYSUM / TURNS
LOCATE 9, 12
PRINT USING "AVE VOLUME/TURN (MBF) = ##.##"; (SUMVOL * 5 /
1000) / TURNS
,
VYHR = ((SUMVOL * 5 / 1000) / TURNS) * (TURNS / (TIME / 45))
,
LOCATE 10, 12
PRINT USING "VOLUME YARDED/HOUR (MBF) = ##.##"; VYHR
,
ROPLIFML = (1 / BENDH) * (TURNS / LIFEML)
ROPLIFHB = (1 / BENDH) * (TURNS / LIFEHB)
,
LOCATE 11, 12
PRINT USING "MAX ML TENSION = ###,###"; MLMAX
LOCATE 12, 12
PRINT USING "MAX HB TENSION = ###,###"; HBMAX
LOCATE 13, 12
PRINT USING "HAULBACK ROPE LIFE (NUMBER OF BENDS) =
###,###"; 2 * TURNS / LIFEHB
LOCATE 14, 12
PRINT USING "MAINLINE ROPE LIFE (NUMBER OF BENDS) =
###,###"; 2 * TURNS / LIFEML
,
BSH = 79500: BSM = 79500: OWNC = 45.47: LAB = 89.25: OPRC =
39.63
COSTHB = HBTOT * 2.51: COSTML = MLTOT * 2.51
HBHR = COSTHB / ROPLIFHB: MLHR = COSTML / ROPLIFML
EQUIPHR = HBHR + MLHR + OPRC + LAB + OWNC
EQUIPMBF = EQUIPHR / VYHR
DESFACHB = BSH / HBMAX: DESFACML = BSM / MLMAX
,
LOCATE 15, 12
PRINT USING "HAULBACK LIFE (HRS) = ##,###"; ROPLIFHB
LOCATE 16, 12
PRINT USING "MAINLINE LIFE (HRS) = ##,###"; ROPLIFML
LOCATE 17, 12
PRINT USING "EQUIPMENT COST PER HOUR = $###.##"; EQUIPHR
LOCATE 18, 12
PRINT USING "EQUIPMENT COST PER UNIT VOLUME = $###.##";
EQUIPMBF
LOCATE 19, 12
PRINT USING "DESIGN FACTOR FOR HAULBACK = ##.##"; DESFACHB
LOCATE 20, 12
PRINT USING "DESIGN FACTOR FOR MAINLINE = ##.##"; DESFACML
IF MPAY = 6000 THEN MLOAD = 16700: HLOAD = 14600
IF MPAY = 8000 THEN MLOAD = 22000: HLOAD = 19000
IF MPAY = 10000 THEN MLOAD = 26500: HLOAD = 23000

```

```

IF MPAY = 12000 THEN MLOAD = 30000: HLOAD = 26000
IF MPAY = 14000 THEN MLOAD = 34000: HLOAD = 30000
IF MPAY = 16000 THEN MLOAD = 38000: HLOAD = 33000
IF MPAY = 18000 THEN MLOAD = 42000: HLOAD = 37000
AVGBML = (2 * MLOAD) / (240000 * .875 * 12)
AVGBDML = (2 * MLOAD) / (240000 * .875 * 1.6 * 12)
AVGBHB = (2 * HLOAD) / (240000 * .875 * 12)
AVGBDHB = (2 * HLOAD) / (240000 * .875 * 1.6 * 12)
AVGNMLTR = (1 / (AVGBML / 1.1012)) ^ (1 / .4871)
AVGDNMLTR = (1 / (AVGBDML / 1.1012)) ^ (1 / .4871)
AVGNHBTR = (1 / (AVGBHB / 1.1012)) ^ (1 / .4871)
AVGDNHBTR = (1 / (AVGBDHB / 1.1012)) ^ (1 / .4871)
AVGPROML = ((1 / AVGNMLTR) + (1 / AVGDNMLTR)) * TURNS
AVGPROHB = ((1 / AVGNHBTR) + (1 / AVGDNHBTR)) * TURNS
AVGLIFML = (1 / BENDH) * (TURNS / AVGPROML)
AVGLIFHB = (1 / BENDH) * (TURNS / AVGPROHB)
AVGHBHR = COSTHB / AVGLIFHB: AVGMLHR = COSTML / AVGLIFML
EQUIPHR1 = AVGHBHR + AVGMLHR + OPRC + LAB + OWNC
EQUIPMBF1 = EQUIPHR1 / VYHR
LOCATE 21, 12
PRINT USING "EQUIPMENT COST PER UNIT VOLUME (AVERAGE) =
$###.##"; EQUIPMBF1
LOCATE 24, 12
INPUT "DO YOU WANT A HARDCOPY OF THE RESULTS (Y/N)"; HCPY$
IF HCPY$ = "Y" OR HCPY$ = "y" GOTO HARDCOPY
END
,
HARDCOPY:
,
LPRINT CHR$(27); CHR$(120); CHR$(1)
LPRINT CHR$(27); CHR$(107); CHR$(0)
LPRINT
LPRINT "
SIMULATION RESULTS"
LPRINT
LPRINT USING "
MAXIMUM PAYLOAD (LBS) = ##,###"; MPAY
LPRINT "
TOTAL TURNS YARDED = "; TURNS
LPRINT "
TOTAL LOGS YARDED = "; SUMLOGS
LPRINT USING "
AVE LOGS PER TURN = #.#"; SUMLOGS / TURNS
LPRINT USING "
TURNS/HR = ##.#"; BENDH
LPRINT USING "
AVE PAYLOAD (LBS) = ###,###"; PAYSUM /
TURNS
LPRINT USING "
AVE VOLUME/TURN (MBF) = ##.##"; (SUMVOL *
5 / 1000) / TURNS
LPRINT USING "
VOLUME YARDED/HOUR (MBF) = ##.##"; VYHR
LPRINT USING "
MAX ML TENSION = ###,###"; MLMAX
LPRINT USING "
MAX HB TENSION = ###,###"; HBMAX
LPRINT USING "
HAULBACK ROPE LIFE (NUMBER OF BENDS) =
###,###"; 2 *

```

```

TURNS / LIFEHB
LPRINT USING "      MAINLINE ROPE LIFE (NUMBER OF BENDS) =
###,###"; 2 * TURNS / LIFEML
LPRINT
LPRINT USING "      HAULBACK LIFE (HRS) = ##,###"; ROPLIFHB
LPRINT USING "      MAINLINE LIFE (HRS) = ##,###"; ROPLIFML
LPRINT
LPRINT USING "      EQUIPMENT COST PER HOUR = $###.##";
EQUIPHR
LPRINT USING "      EQUIPMENT COST PER UNIT VOLUME =
$###.##"; EQUIPMBF
LPRINT USING "      EQUIPMENT COST PER UNIT VOLUME (AVERAGE)
= $###.##"; EQUIPMBF1
LPRINT
LPRINT USING "      DESIGN FACTOR FOR HAULBACK = ##.##";
DEFACHB
LPRINT USING "      DESIGN FACTOR FOR MAINLINE = ##.##";
DEFACML
LPRINT CHR$(27); CHR$(120); CHR$(0)
LPRINT CHR$(12)
END
'
CALC:
'
'      ** DETERMINE GEOMETRY **
'
THB = 2000
INC = 2000
CL = 40
'
ITER:
'
YYY = Y(PX(K)) + ((A(PX(K) + 1) / 100) * (X - X(PX(K))))
DL = X - X(TP1): DR = X(TP2) - X
HL = Y(TP1) + HS1 - CL - YYY
HR = Y(TP2) + HS2 - YYY - CL
GOSUB DRUMRAD
IF PX(K) > 0 THEN GOTO INLOOP
'
'      ** COMPUTE SEGMENT FORCES **
'
'      ** SEGMENT #1 - SKYLINE LEFT **
'
TU = TA: D = DL: HTT = HL: WTT = WA
GOSUB RIGLNK
V11 = VL: H11 = HC
'
'      ** SEGMENT #2 - SKYLINE RIGHT **
'
IF HR > 0 THEN TU = TA - (WA * (Y(TP1) + HS1 - Y(TP2) -
HS2)): HTT = HR

```

```

IF HR < 0 THEN TU = TA - (WA * HL): HTT = -HR
D = DR: WTT = WA
GOSUB RIGLNK
H22 = HC
IF HR > 0 THEN V22 = VL
IF HR < 0 THEN V22 = -(VL + (WA * S))
/
/      ** SEGMENT #4 - HAULBACK **
/
IF HR > 0 THEN TU = T4 - WH4 * HL + WH4 * HR: HTT = HR
IF HR < 0 THEN TU = T4 - WH4 * HL: HTT = -HR
D = DR: WTT = WH4
GOSUB RIGLNK
H44 = HC
IF HR > 0 THEN V44 = VL
IF HR < 0 THEN V44 = -(VL + WH4 * S)
/
/      ** SEGMENT #3 - MAINLINE **
/
H33 = H22 + H44 - H11
S3 = SQR(DL ^ 2 + HL ^ 2)
V33 = H33 * HL / DL - .5 * WMS * S3
T3 = SQR(H33 ^ 2 + (V33 + WMS * S3) ^ 2)
/
/      ** DETERMINE NET PAYLOAD **
/
PAY = (V11 + V22 + V33 + V44 - CW) - WLOAD
IF ABS(PAY) < 100 THEN GOTO TT
IF PAY < 0 THEN THB = THB + INC: GOTO ITER
IF PAY > 0 THEN THB = THB - INC
INC = INC / 2: GOTO ITER
/
TT:
/
GOSUB TORQUE
INHAUL1 = INHAUL1 + (SQR(X ^ 2 + (Y(TP1) + HS1 - YYY - CL) ^
2)) / MLDLS
BML1 = (2 * T3) / (240000 * .875 * 12)
BDML1 = (2 * T3) / (240000 * .875 * RML * 12)
NML1TR = (1 / (BML1 / 1.1012)) ^ (1 / .4871)
NDML1TR = (1 / (BDML1 / 1.1012)) ^ (1 / .4871)
NML1TR = (1 / NML1TR) + (1 / NDML1TR)
NML1 = NML1 + NML1TR
BHB1 = (2 * SQR(V11 ^ 2 + H11 ^ 2)) / (240000 * .875 * 12)
BDHB1 = (2 * SQR(V11 ^ 2 + H11 ^ 2)) / (240000 * .875 * RHB
* 12)
NHB1TR = (1 / (BHB1 / 1.1012)) ^ (1 / .4871)

```



```

H22 = HC
IF HR > 0 THEN V22 = VL
IF HR < 0 THEN V22 = -(VL + (WA * S))
,
,
** SEGMENT #4 - HAULBACK **
,
IF HR > 0 THEN TU = T4 - WH4 * HL + WH4 * HR: HTT = HR
IF HR < 0 THEN TU = T4 - WH4 * HL: HTT = -HR
D = DR: WTT = WH4
GOSUB RIGLNK
H44 = HC
IF HR > 0 THEN V44 = VL
IF HR < 0 THEN V44 = -(VL + WH4 * S)
,
,
** SEGMENT #3 - MAINLINE **
,
H33 = H22 + H44 - H11
S3 = SQR(DL ^ 2 + HL ^ 2)
V33 = H33 * HL / DL - .5 * WMS * S3
T3 = SQR(H33 ^ 2 + (V33 + WMS * S3) ^ 2)
,
,
** DETERMINE NET PAYLOAD **
,
PAY = (V11 + V22 + V33 + V44 - CW) - WLOAD
IF ABS(PAY) < 100 THEN GOTO TTT
IF PAY < 0 THEN THB = THB + INC: GOTO NEWHL
IF PAY > 0 THEN THB = THB - INC
INC = INC / 2: GOTO NEWHL
,
TTT:
,
GOSUB TORQUE
IF T3 > MLMAX THEN MLMAX = T3: DRML = RML
TNSHB2 = SQR(V11 ^ 2 + H11 ^ 2)
IF TNSHB2 > HBMAX THEN HBMAX = TNSHB2: DRHB = RML
IF I = TP1 + 1 THEN INHAUL2 = INHAUL2 + ((SQR(X(I) ^ 2
+ (Y(TP1) - Y(I)) ^ 2)) / MLDLS): GOTO LAST
INHAUL4 = INHAUL4 + ((SQR((X(I) - X(I - 1)) ^ 2 + (Y(I)
- Y(I - 1)) ^ 2)) / MLDLS)
BML2 = (2 * T3) / (240000 * .875 * 12)
NML1TR = (1 / (BML2 / 1.1012)) ^ (1 / .4871)
BDML2 = (2 * T3) / (240000 * .875 * RML * 12)
NDML1TR = (1 / (BDML2 / 1.1012)) ^ (1 / .4871)
NML1TR = (1 / NML1TR) + (1 / NDML1TR)
NML2(I) = NML2(I) + NML1TR
BHB2 = (2 * TNSHB2) / (240000 * .875 * 12)

```

```

      NHB1TR = (1 / (BHB2 / 1.1012)) ^ (1 / .4871)
      BDHB2 = (2 * SQR(V11 ^ 2 + H11 ^ 2)) / (240000 * .875 *
RHB * 12)
      NDHB1TR = (1 / (BDHB2 / 1.1012)) ^ (1 / .4871)
      NHB1TR = (1 / NHB1TR) + (1 / NDHB1TR)
      NHB2(I) = NHB2(I) + NHB1TR
      NEXT I
    ,
LAST:
    ,
INHAUL3 = INHAUL3 + ((SQR((X - X(PX(K))) ^ 2 + (Y(PX(K)) -
YYY) ^ 2)) / MLDLS)
GOTO PRINTOP
    ,
DRUMRAD:
    ,
LHB = HBTOT - HS1 - (SQR(DL ^ 2 + HL ^ 2)) - (2 * SQR(DR ^ 2
+ HR ^ 2))
LML = MLTOT - HS1 - SQR(DL ^ 2 + HL ^ 2)
NHB = (-16 + SQR(16 ^ 2 + .875 ^ 2 * LHB / (.2618 * 30))) /
.875
NML = (-16 + SQR(16 ^ 2 + .875 ^ 2 * LML / (.2618 * 30))) /
.875
IF NHB - INT(NHB) > 0 THEN NHB = INT(NHB) + 1
IF NML - INT(NML) > 0 THEN NML = INT(NML) + 1
RHB = (16 + (NHB * .875) - (.5 * .875)) / 12
RML = (16 + (NML * .875) - (.5 * .875)) / 12
MHB = THB * 12 * RHB: TA = THB + HS1 * WA: T4 = TA
RETURN
    ,
RIGLNK:
    ,
S = SQR(D ^ 2 + HTT ^ 2)
HC = TU * D / S * SQR(1 - (.5 * WTT * D / TU) ^ 2) - .5 *
WTT * D * HTT / S
VL = HC * HTT / D - .5 * WTT * S
RETURN
    ,
TORQUE:
    ,
TTMLHB = ((MHB / 12) * .98 * .98) / ((114 / 28) * (28 / 90))
MLTENG = ((T3 - WMS * HS1) * RML) - TTMLHB
RET = MLTENG / (10 * .85)
NENG = (3700 - RET) / 1.733
NMLD = NENG / 10
IF PX(K) = 0 THEN MLDLS = 100
IF PX(K) > 0 THEN MLDLS = (2 * 3.1416 * RML * NMLD)
RETURN

```

## APPENDIX B

### PACE PROGRAM

PACE (Production And Cost Evaluation) is a program developed by Dr. John Sessions at Oregon State University [4] which is used for determining harvesting cost appraisals. One portion of the program computes machine owning and operating costs based on conditions related to such items as initial purchase price, interest rate, depreciation period, labor rates, etc. In this paper, machine rates for a yarder are calculated. The following input was used:

- 1) Initial Purchase Price of Yarder = \$500,000.00
- 2) Salvage Value of Yarder = 20% of purchase price
- 3) Yarder Life (years) = 8.0
- 4) Days Yarder Worked/Year = 200.0
- 5) Hours Yarder Worked/Day = 8.0
- 6) Annual Interest Expense = 4.0%
- 7) Percent Avg Annual Invest for Taxes, License, Etc = 3.0%
- 8) Labor, Number of Workers = 5
- 9) Travel Hours/Day = 2.0
- 10) Operating Hours/Day = 8.0
- 11) Percent Direct Labor for Supervision = 5.0%
- 12) Percent Equipment Depreciation for Repairs = 50%
- 13) Fuel Consumption, Gallons/Hour = 15.00
- 14) Fuel Cost/Gallon = \$1.00
- 15) Percent of Fuel Consumption for Lubricants = 5.0%
- 16) Cost/Gallon of Lubricants = \$12.00

17) Cost of Lines = \$15,750 (haulback & mainline)

18) Estimated Line Life (Hours) = N/A \*\*

\*\* The line life is the variable factor in determining the equipment cost per hour. Since for each maximum logload simulated a different line life is obtained, this value will vary. Therefore, the equipment cost per hour produced by PACE will not include the line cost per hour. The simulation program will compute the line lives and determine their costs per hour. This cost will then be added to the PACE result for the total equipment cost per hour.

The above parameters are input into the PACE model and the program is executed. The results of the PACE output for equipment ownership cost, labor, and equipment operating cost are attached to this appendix. The overall equipment rate (minus wire rope cost) is \$174.34/hr.

### Equipment Ownship Costs

|   |               |
|---|---------------|
| Delivered equipment cost  | \$ 500,000.00 |
| Minus line and rigging cost   | \$ 0.00       |
| Minus tire or track replacement cost  | \$ 0.00       |
| Minus residual (salvage) value  | \$ 100,000.00 |
| Life of equipment (years)   | # 8.00        |
| Number of days worked per year  | # 200.00      |
| Number of hours worked per day  | # 8.00        |
| Interest expense  | % 4.00        |
| Percent of avg annual investment for:<br>Taxes, License, Insurance, and Storage | % 3.00        |
| <hr/>   |               |
| Depreciable value:  | \$ 400,000.00 |
| Equipment depreciation:   | \$ 50,000.00  |
| Average annual investment:  | \$ 325,000.00 |
| Interest expense:   | \$ 13,000.00  |
| Taxes, license, insurance, & storage:   | \$ 9,750.00   |
| Annual ownership cost:  | \$ 72,750.00  |
| Annual utilization (Hours per year):  | # 1,600.00    |
| Ownership cost (Dollars per hour):  | \$ 45.47      |

### Equipment Operating Costs

|  |          |
|--|----------|
| Percent equip depreciation for repairs | % 50.00  |
| Fuel amount (Gallons per hour)         | # 15.00  |
| Fuel cost (Per gallon)                 | \$ 1.00  |
| Percent consumption for lubricants     | % 5.00   |
| Cost oil and lubricants (Per Gallon)   | \$ 12.00 |
| Cost of lines                          | \$ 0.00  |
| Estimated life of lines (Hours)        | # 0.00   |
| Cost of rigging                        | \$ 0.00  |
| Estimated life of rigging (Hours)      | # 0.00   |
| Cost of tires or tracks                | \$ 0.00  |
| Estimated life of tires/tracks (Hours) | # 0.00   |
| <hr/>                                  |          |
| Repair and maintenance:                | \$ 15.63 |
| Fuel:                                  | \$ 15.00 |
| Oil and lubricants:                    | \$ 9.00  |
| Lines:                                 | \$ 0.00  |
| Rigging:                               | \$ 0.00  |
| Tires or tracks:                       | \$ 0.00  |
| Equipment operating cost (Subtotal):   | \$ 39.63 |

Pace Output

### Labor Costs

|  |    |       |
|--|----|-------|
| Base wage 1st crew position (Per hour) | \$ | 15.00 |
| Base wage 2nd crew position (Per hour) | \$ | 14.00 |
| Base wage 3rd crew position (Per hour) | \$ | 12.00 |
| Base wage 4th crew position (Per hour) | \$ | 12.00 |
| Base wage 5th crew position (Per hour) | \$ | 15.00 |
| Base wage 6th crew position (Per hour) | \$ | 0.00  |
| Fringe benefits                        | %  | 0.00  |
| Travel time per day (Hours)            | #  | 2.00  |
| Operating time per day (Hours)         | #  | 8.00  |
| Percent direct labor for supervision   | %  | 5.00  |

---

|  |    |        |
|--|----|--------|
| Total number of workers:               | #  | 5.00   |
| Total crew wage (Per hour):            | \$ | 68.00  |
| Direct labor cost:                     | \$ | 85.00  |
| Supervision and overhead:              | \$ | 4.25   |
| Labor cost (Subtotal):                 | \$ | 89.25  |
| Total operating cost (Operating+Labor) | \$ | 128.88 |

### Summary

#### \*\*\* YARDING SIMULATION EQUIPMENT \*\*\*

|                                       |    |                  |
|---------------------------------------|----|------------------|
| Ownership                             |    |                  |
| Depreciable value:                    | \$ | 400,000.00       |
| Equipment depreciation:               | \$ | 50,000.00 / Year |
| Interest expense:                     | \$ | 13,000.00 / Year |
| Taxes, license, insurance, & storage: | \$ | 9,750.00 / Year  |
| Annual ownership cost:                | \$ | 72,750.00 / Year |
| Ownership cost (Subtotal):            | \$ | 45.47 / Hour     |
| Machine operating                     |    |                  |
| Repairs and maintenance:              | \$ | 15.63 / Hour     |
| Fuel and oil:                         | \$ | 24.00 / Hour     |
| Lines and rigging:                    | \$ | 0.00 / Hour      |
| Tires or tracks:                      | \$ | 0.00 / Hour      |
| Equipment operating cost (Subtotal):  | \$ | 39.63 / Hour     |
| Labor                                 |    |                  |
| Direct labor cost:                    | \$ | 85.00 / Hour     |
| Supervision and overhead:             | \$ | 4.25 / Hour      |
| Labor cost (Subtotal):                | \$ | 89.25 / Hour     |
| OWNERSHIP COST                        | \$ | 45.47 / Hour     |
| OPERATING COST                        | \$ | 39.63 / Hour     |
| LABOR COST                            | \$ | 89.25 / Hour     |
| Machine rate (Own+Oper+Labor)         | \$ | 174.34 / Hour    |

Pace Output

APPENDIX C

LINE STRETCH CALCULATIONS

The work done when a wire rope is stretched can be determined by recalling that in the linear region (Figure 10),  $s = f(T) = mT$ :

$$s = \frac{T*(S_o)}{A*E} \quad \text{EQ. 1}$$

Where:  $s$  = the line stretch in feet

$T$  = the tension in the line (lb)

$S_o$  = the initial length of the line

$A$  = the metallic area of the wire rope (sq. in.)

$E$  = the modulus of elasticity of the wire rope

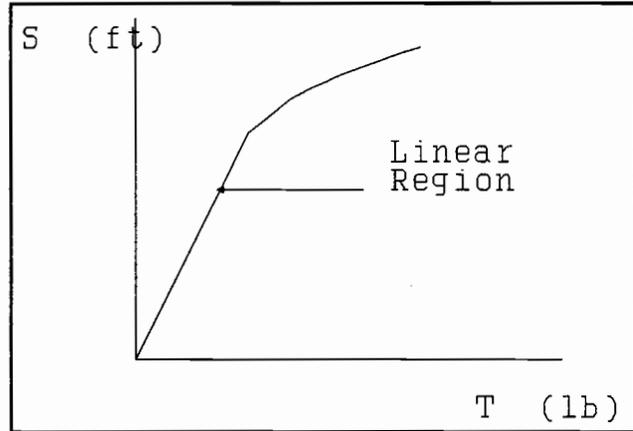


Figure 9. Wire Rope Stretch.

The work done is:

$$W = \int_0^s T(ds) \quad \text{EQ. 2}$$

Setting  $m = S_o/AE$  and solving for  $T = s/m$ , we have:

$$W = \int_0^s \frac{s(ds)}{m} \quad \text{EQ. 3}$$

Performing the integration we get:

$$W = \frac{s^2}{2m} \quad \text{EQ. 4}$$

Substituting from  $s = mT$  into EQ. 4, the result is:

$$W = \frac{Ts}{2} \quad \text{EQ. 5}$$

Where:  $T$  = the tension that caused the stretch,  $s$