PRODUCTIVITY, COSTS, AND OPTIMAL SPACING OF SKYLINE CORRIDORS OF TWO CABLE YARDING SYSTEMS IN PARTIAL CUTTING OF SECOND-GROWTH FORESTS OF COASTAL BRITISH COLUMBIA

by

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Abstract

Public pressure to end clearcut logging, and changing forest management needs have increased opportunities for partial cutting in British Columbia’s second-growth coastal forests. Production economics and engineering design of cable harvesting systems for partial cutting in second-growth forests of British Columbia (BC) are largely unknown. Scientific research and working experience in partial cutting forest harvesting operations in coastal areas of the Pacific Northwest of North America is from the United States or from selection harvesting of old growth forests in coastal BC prior to 1935.

Time and motion studies were conducted in fall of the 1992 and spring of 1993 on two cable yarders in second growth coastal forests (on Vancouver Island) of BC. The goals of the studies were to design a forest engineering system for field layout of cable harvesting systems in partial cutting, develop production and cost models for the two yarders, compare the productivity and costs of partial cutting and clearcutting, and develop models for optimal spacing of skyline yarding corridors.

Results showed that forest engineering of partial cutting with cable yarders was dependent upon corridor spacing and tailspar tree location, size and species. Production and cost analyses showed that wider corridors and larger crew sizes were more efficient, but also that productivity gains from larger crew sizes did not result in lower operating costs. Clearcutting in all instances was shown to be more efficient and cost effective than partial cutting. The coastal stumpage appraisal system was shown to vastly under-estimate the added costs of partial cutting in relation to clearcutting. Optimal skyline corridor analysis and comparisons demonstrated that lower
variable yarding costs resulted from wider corridor spacing, both contractors spaced yarding
corridors narrower than optimal, and costs could be reduced by optimal spacing of corridors. The
quantity of timber harvested with partial cutting is increasing annually, and knowledge and
experience in these harvesting systems is necessary and will be an asset.
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INTRODUCTION

The impact of intellectual and physical urban sprawl\(^1\) which has reduced the allowable levels of clearcutting, and changing forest management needs have increased opportunities for partial cutting in British Columbia's second-growth coastal forests. Production economics and engineering design of cable harvesting systems for partial cutting in second-growth forests of British Columbia (BC) are largely unknown. Nearly 100 years of experience is available for clearcutting old-growth, much of which is directly applicable to clearcutting of second-growth stands. However, forest engineers have limited knowledge and training in design and layout of partial cutting operations, and few published reports on the topic are available. Past research and recent trials of partial cutting in second-growth have dealt primarily with ecological and silvicultural implications. Engineering and economic considerations have generally been ignored in these studies. Partial cutting with cable systems presents a unique challenge where minimising production costs and controlling damage to the residual stand must be carefully balanced to achieve both economic and silvicultural objectives.

The foundation of production economics in forestry is the field study of forest operations and system productivity and costs. Production economics of forestry operations relate performance based on the consumption of time by equipment and labour to measurements of forestry, terrain, and climatic conditions. This information is invaluable to the planning and scheduling of forest operations. One of the most important planning considerations in partial cutting operations with cable harvesting systems is the spacing of skyline Yarding corridors. It has been shown in past studies that corridor spacing directly influences the profitability of

\(^1\) "Intellectual urban sprawl" is the influence the urban perception has on forest management and government regulations.
operations, the residual stand spacing, and the quantity of site and residual stand damage. The focus of this report is fourfold: first, to design a system of engineering yarding corridors for cable harvesting systems in partial cuts; second, to perform field studies for economical analysis of cable harvesting systems in partial cuts; third, to develop optimal skyline corridor spacing models based on minimising harvest system costs; and four, to investigate the impact of skyline corridor width on production.

An extensive literature review of partial cutting systems and alternative silvicultural systems for coastal forests of the North American Pacific Northwest was published by Howard et al. (1993), however the majority of the information is focused in the Pacific Northwest of the United States, not BC. Field trials and analysis of field trials are required for coastal BC.

Previous studies indicate that minimisation of total harvesting costs through optimum road and landing spacing is one of the most important economic parameters in forest engineering. Many studies explore this relationship, but are restricted mostly to clearcutting systems. Similarly, optimum cable yarding corridor spacing is an important economic consideration in development and management of partial cutting cable harvesting systems: it is a function of moving costs (fixed) of the yader, and lateral yarding costs (variable). Discussion of this relationship was not found in previous studies.

The goal of this report is to study cable harvesting systems in partial cutting of second growth forests of British Columbia and develop productivity, cost, and optimal skyline corridor spacing models from field trials, and test the impact of skyline corridor width on production and costs. The optimal corridor spacing model and data collected from field trials will be used to compare optimal corridor spacing and costs to the actual observed values. It is hoped that the
production information and models, and the optimal corridor spacing model will provide sensible, practical guidelines to be used by forest managers, to make informed decisions concerning partial cutting. Objectives set to achieve this goal are:

1. Develop a system of field engineering for partial cutting with cable harvesting equipment.
2. Determine if corridor width has an impact on yarding production and costs.
3. Perform production studies of two cable harvesting systems partial cutting in second growth forests of coastal British Columbia in order to investigate the relationship between cost, productivity, and skyline corridor width and spacing.
4. Develop models for predicting the production and costs of two cable yarding systems.
5. Compare and contrast the production and costs of partial cutting and clear cutting with cable yarding systems.
6. Derive a mathematical model for optimal corridor spacing, and explore the impacts of corridor spacing on cable harvesting systems in partial cutting of second growth forests of coastal BC.
7. Compare optimal and actual costs of two cable systems from data collected in the field.

To meet these objectives the study was divided into four components which are presented here separately. First, a literature search was conducted to review previous research on optimal spacing of skyline corridors in partial cuts. The second section is a description of the field studies and analysis methodology including: site selection, harvest layout and engineering, time study design, cost analysis, productivity and cost models, and development of the optimal skyline
yarding corridor model. Third, is a discussion of the results from the: statistical analysis, development of production functions, production models, cost analyses, comparison of productivity and costs of partial and clearcutting, and development and examples of the optimal yarding corridor model. Lastly, conclusions of the results and recommendations are presented.

1.0 Literature Review

The objective of the literature search was to investigate past research on optimal spacing and width of yarding corridors. The literature search is divided into five parts: optimal road spacing, optimal road and landing spacing, optimal corridor spacing, corridor width, and average yarding distance. Average yarding distance is used in estimating costs and productivity of lateral yarding, and therefore essential for calculating optimal spacing. The scope of the literature review is not restricted to cable yarding in young or second growth forests of the Pacific Northwest of North America, because few previous studies exist, and mathematical principles of optimal spacing are similar from region-to-region, and from harvesting system-to-harvesting system. Articles from each section are presented chronologically.

1.1 Optimal Road Spacing

Matthews (1942) provided the first models of controlling logging costs based on optimal spacing of forest roads. Matthews compared the harvesting costs within a tract of timber with long skidding distances from a main road to the harvesting costs of constructing arteriole roads
and shortening the skidding distance. The purpose of this comparison was to find the optimal road spacing which minimized total harvesting costs by balancing road construction and skidding costs. Based on this comparison he showed that total harvesting costs could be expressed as a function of the skidding costs per unit distance, the fixed cost of road construction per unit distance, and the volume of timber per unit area accessed by road construction. The resultant equation is as follows:

\[ X = C \frac{S}{4} + \frac{R}{VS} \]  

where: 
- \( X \) = Total harvesting costs per unit product
- \( C \) = Skidding costs per unit product per unit distance
- \( S \) = Road spacing per unit distance
- \( R \) = Road construction costs per unit distance
- \( V \) = Volume of product per unit area

Each cost component in Matthew’s model is a function of road spacing: skidding costs vary directly with changing values of road spacing, and road construction costs vary inversely with changing road spacing values. Though not well explained in his text, Matthews developed a model for optimal road spacing by equating the fixed costs of road construction to variable skidding costs, and solved for road spacing (\( S \)) as follows:

\[ S = \frac{4R}{\sqrt{VC}} \]  

Peyton (1973) developed an optimal road spacing model for ground skidding in Newfoundland (Canada). Peyton’s model was similar to Matthews (1942) in that the total cost equation was divided into the fixed costs of road construction, and the variable costs of production. The total cost equation was minimised with respect to road spacing, and optimal...
spacing was solved in terms of fixed and variable cost. Peyton used area instead of average skidding distance to formulate the equation. The result was the following equation:

\[ S = \sqrt{\frac{LR}{2dct(1+P)}} \]  

Eq. [3]

where:  
- \( S \) = road spacing  
- \( d \) = volume / area  
- \( c \) = cost / minute of skidding  
- \( t \) = time to travel and return linear distance  
- \( L \) = load size  
- \( R \) = road cost  
- \( P \) = delays as a percent of travel time

He suggested that optimal road spacing will lead to optimum road quality, because the optimum amount spent on road construction will be balanced by the cost per unit volume to harvest timber.

Accurate determination of variables, variables changing within the block, and the lack of consideration for the number of trees per unit volume, were some of the difficulties with the optimal road spacing model discussed by Peyton. He also presented a field and office work program for proper road spacing, by explaining the planning process in sequential steps.

Huggard (1978) presented data from 1950 to 1978 on average and optimal road spacing. He suggested that road density was high in the past; because methods of planning forest road spacing were crude, and based on historic, not future machine capabilities. Solutions to optimal road spacing were shown graphically, based on an equation that equates road cost and production, to operational costs and efficiency. Results showed that road spacing had increased 350 percent in 28 years, because increased payload size and equipment speed had lowered operating costs. The graphical solution illustrates road spacing levelling off in the last 10 years of the study, and that optimal road spacing may be approaching its practical limits.
In their textbook “Logging and Pulpwood Production” Stenzel et al. (1985) define road spacing as the distance between parallel roads that gives the lowest cost per unit volume of production and road construction. According to the authors optimum road spacing and variable costs of yarding equate to fixed costs of road construction. They provide graphical solutions to this problem, and warn that optimal spacing is only a guide, and the determining factor in road spacing is balancing machine capacity, productivity, and topography.

Yeap and Sessions (1988) present a numerical technique for determining optimal spacing of local and collector roads on uniform terrain, similar to that of Matthews (1942). Their methods differed from previous models in five aspects:

1. Skidding costs could be non-linear;
2. The spacing model could be extended over multiple periods;
3. A choice of four skidding patterns was provided;
4. Fixed costs were based on average and not total road construction costs; and
5. Hooke and Jeeves pattern of search was used, avoiding taking derivatives of the average cost equation.

The report provided detailed formulation of the cost equation based on total skidding, transport, and road construction costs. Examples demonstrated the influence of volume harvested on road spacing, using a right angle skidding pattern, and linear skidding costs. The results showed that narrower road spacing was possible, when increased volume per unit area was harvested, driving down the cost of logging.

Instead of minimising costs like previous researchers, Thompson (1988) defined each component of the profit function in relation to road spacing, and used linear programming to
develop a mathematical model for optimal road spacing based on maximising profits. The impact of varying product value (market price) and cost minimisation on road spacing was demonstrated with an example. Results showed that it is advantageous to increase road construction costs in order to maximise profits and productivity. The model was based on, and compared to Matthew's (1942) model for “two-way” yarding. Thompson’s model had narrower and fluctuating values of road spacing compared to Matthews because it tracks product value rather than cost minimisation.

Unlike previous studies, Sessions and Yeap (1989) attempted to provide a general solution for optimal road spacing which could be used by landowners for allocation of skidding and road building equipment among several areas. These researchers derived and compared road spacing from revenue, non-linear skidding costs, and the profit potential of equipment operation. They assumed a two-way perpendicular skidding pattern. An example of their model showed that optimal road spacing and skidding and road construction allocation were directly affected by timber volume, road construction rates, variable skidding costs, equipment production, and opportunity costs of the contractor’s equipment.

Howard and Kriese (1990) used Matthews (1942) model for optimal road spacing for two way skidding, and a time study of grapple skidding operations to determine economical optimal road spacing. The results from the time study are shown, including presentation of regression models. Regression equations from the time study, and an equation for average skidding distance were incorporated into the total cost function. The operating costs were minimised with respect to road spacing in the total cost function, and an iterative process was used to solve for road spacing. The solution to an example was provided graphically, showing the non-linear
relationship between skidding costs and road spacing. The graph shows that a single road spacing is not optimal for every stand, but is a range of values dependent upon construction costs, and volume of harvested timber. Another graph shows the relationship between optimal road spacing and construction costs at various harvest levels.

Howard and Tanz (1990) developed equations needed to determine the economically optimal spacing of roads for multi-stage, one way yarding to roadside. Multi-stage yarding are forest operations that utilise two or more logging systems for primary transportation of timber. Matthews (1942) total cost equation for one way yarding to roadside was modified to formulate optimal road spacing equations for two and three stage yarding. Using regression models from four grapple yarders, a super snorkel, and dropline yarding, road spacing was estimated for single, two, and three stage cable yarding operations. Results showed that road spacing increased dramatically with increased road construction costs. Two stage yarding was cheaper and had wider road spacing than single stage yarding, and three stage was cheaper and had wider road spacing than two stage yarding, once a certain level of road construction costs were exceeded.

1.2 Optimal Road and Landing Spacing

Matthews (1942) also developed models for optimising both road and landing spacing. Like his road spacing models, he expressed optimal spacing as a function of road construction costs and landing construction and moving costs (both fixed) and lateral yarding costs (variable). He presented the following total cost equation for two-way skidding:

\[ X = PCS + \frac{R}{VS} + \frac{L}{VLS} \]  

Eq. [4]
Where: 

- \( X \) = Total harvesting costs per unit product
- \( P \) = Average skidding distance
- \( C \) = Skidding costs per unit product per unit distance
- \( S \) = Road spacing per unit distance
- \( R \) = Road construction costs per unit distance
- \( V \) = Volume of product per unit area
- \( L \) = Landing cost per unit product
- \( LS \) = Landing Spacing

He provided a direct solution for optimal spacing similar to his road spacing problem, by equating the fixed costs of landing and road construction to variable skidding costs. Like the road spacing models Matthews equates fixed and variable costs and solves for road and landing spacing. The resultant equations were:

\[
S = \frac{\sqrt{R/C}}{P}\quad \text{Eq. [5]}
\]

\[
LS = \frac{\sqrt{L/C}}{P}\quad \text{Eq. [6]}
\]

For these equations to apply Matthews made some basic assumptions: yarding occurs in a straight line, harvesting costs vary linearly with distance, and timber and logs are distributed evenly over the area.

Carter et al. (1973) attempted to expand upon Matthews (1942) optimal road spacing model by compiling extremely detailed cost data, including voluminous information on eight cost variables included in the total cost equation. The researchers expressed all of the total cost equation variables in terms of road and landing spacing, and minimised the total cost equation with respect to road and landing spacing. Optimal road and landing spacing were then solved simultaneously, using a computer based iteration process. The model was used to show optimal road and landing spacing for logging with a medium and large crawler tractor.
Peters (1978) expanded upon Matthews (1942) formulation for road and landing optimal spacing to minimise timber harvest cost. To increase the accuracy of Matthews model, Peters used the radial distance approach developed by Suddarth and Herrick (1964) to calculate average skidding distance. Using an example, the two methods are compared using clearcut and selective harvest methods. The results suggest that average skidding distance based on the Suddarth and Herrick approach, yields slightly more accurate results than Matthews, and that the expected decrease in volume of timber extracted from selective harvests, will result in significantly higher costs and narrower road and landing spacing.

Unlike Matthews (1942) approach of expressing skidding costs as a function of average skidding distance for an entire block, Sessions and Guangda (1987) solved for optimal spacing by summing skidding costs from readily identifiable rectangular subareas. By estimating skidding costs from sub-units, it was not necessary to calculate average skidding costs, and linear and non-linear skidding costs were treated with equal ease. Six computer programs were used to solve four classes of road and landing spacing by summing average skidding costs for sub-areas.

1.3 Optimal Yarding Corridor Spacing

Wettstein (1965) discussed economic spacing of skyline yarding corridors in terms of transportation costs and “installation” costs. He stated that optimal spacing was limited to these cost expenditures. Installation costs were the fixed costs of moving and setting up the yarder, and are considered independent of production, and transport costs were those factors which varied with production.
Bhalla and Svanqvist (1968) were among the first researchers to model optimal spacing based on curvilinear harvesting costs. They used an iterative cost minimisation approach similar to Matthews (1942) to solve for optimal corridor spacing. Their model required an estimate of volume per setting, production estimates at varying distances from the skyline corridor, and an estimate of the fixed costs of moving. An iterative model was used to compute the optimal solutions. Solutions to the model were presented at 10 m intervals from the skyline corridor. Results showed that small gains are possible through optimisation: there was only a 10 percent difference between optimum and the maximum distances. The major shortcomings of this study were that production and cost data used to illustrate the model were hypothetical, and the model does not provide set-up and moving costs.

Omnes (1980) estimated optimal yarding corridor spacing by breaking the cable yarding production cycle into time components which directly affected yarding corridor spacing: lateral yarding and set-up. He estimated lateral yarding and set-up costs from field trials in gentle and rugged terrain, and with different rigging configurations, and derived optimal yarding corridor spacing by assessing the impact of these factors on total cost. Conclusions from the study suggested that terrain and rigging configuration significantly influence lateral yarding and optimal yarding corridor spacing. A generalised model for yarding corridor spacing was not developed.

Samset (1990) summarised time and performance studies carried out by the Forest Operations Division of the Norwegian Forest Research Institute, from 1947 to 1989. Samset discusses work tasks or activities in forest operations in terms of sequences, whereby work or actions are performed in the form of a process. The process is a system of work elements which can be timed in order to measure the performance of the process. To demonstrate the use of time
studies in forest operations, Samset used the example of a small cable yarder, and optimal spacing of skyline yarding corridors in clearcutting. The work sequence was broken down into time elements and the associated site variables including yarding corridor length ($L_1$), average corridor yarding distance ($L_T$; where $L_1 = 2 \times L_T$), average lateral yarding distance (sk), corridor spacing ($B$: where $B = 2 \times sk$), average load size ($v$), number of trees per load ($n$: which was 3 logs), volume per unit area, and the fixed time of rigging the cable yarder ($m^3$/hour). Samset, like Matthews and other previous authors, presented the work sequence equation in terms of it's time elements and variables (Eq. 7), and solved optimal skyline yarding by differentiating the equation with respect to corridor spacing and setting the derivative equal to zero (Eq. 8).

$$W_o = \frac{10.4 \times L_1 + L_T}{B \times L_1 \times V} + 0.000117 \times L_1 + 0.00054 \times B + 0.068$$  \hspace{1cm} \text{Eq. [7]}

$$B = \sqrt[3]{19259 \times \frac{1}{V} + 370370 \times \frac{1}{L_1 \times V}}$$  \hspace{1cm} \text{Eq. [8]}

Samset used an example to show two important characteristics of his performance model: first, that spacing between corridors was dependent upon the volume per hectare and the lateral yarding time, and second that yarding corridor length had little influence on yarding corridor spacing.

McNeel and Young (1994) developed an analytical model for determining optimal yarding corridor width (landing spacing), assuming a constant external yarding distance and zero percent slope perpendicular to the yarding corridor. The model is based on estimates of lateral yarding times and road change times from time and motion studies of conventional skyline yarders in coastal British Columbia. McNeel and Young, like Samset (1990), developed an equation for
total cycle time that was derived from regression coefficients of choking times (time to choke logs during lateral yarding), lateral yarding times based on average lateral yarding distance, and the fixed time of changing yarding corridors. Both studies assumed that other elements of the work cycle did not influence lateral yarding times, and were not included in the model. The total yarding time equation based on the lateral yarding component and the fixed time of changing yarding corridors is as follows:

\[ TC = [\beta_0 + \beta_1 \times \left(\frac{YRW}{6}\right)] + \left[MT \times \left(\frac{EEB}{YRW \times CT}\right)\right] \]  

Eq [9]

where:
- \( TC \) = total time contributed by choke and move elements (min. per cycle)
- \( \beta_0 \) = sum of regression constants for lateral yarding
- \( \beta_1 \) = sum of regression coefficients for lateral yarding
- \( YRW \) = yarding road width (m) (corridor spacing)
- \( MT \) = mean yarding corridor change time per occurrence (min.)
- \( EEB \) = effective external boundary
- \( CT \) = total number of yarding cycles required to yard harvest unit

To develop the yarding corridor spacing model, Eq [9] was minimised with respect to yarding corridor spacing and set to zero. The equation was rationalised, and the following equation for yarding corridor spacing was developed:

\[ YRW = \sqrt{\frac{6 \times MT \times EEB}{\beta_1 \times CT}} \]  

Eq [10]

McNeel and Young tested the equation using field data, and showed that under the constraints of the field study the optimal spacing of skyline corridors for a conventional skyline yarder was 45 m. Results from the analysis were presented in graphical form, and showed that decreasing or increasing the yarding corridor spacing by 10 m had little effect on total costs. The results of further analysis showed that increasing the moving and set-up time of the yarder by 100 percent increased optimal yarding corridor spacing by 33 percent, and McNeel and Young conclude that
the value for optimal yarding road width is relatively insensitive to changes in moving and set-up times of the cable yarders.

1.4 Skyline corridor width

There were no previous studies found on skyline corridor width.

1.5 Average Yarding / Skidding Distance

The earliest work on average skidding distance was done by Matthews (1942), however the first detailed formulation of the problem was presented by Suddarth and Herrick (1964). They formulated equations for circular and rectangular harvest areas based on a planar function which assumes that all skidding is in a straight line from stump to landing, and that logs are distributed evenly over the skidding area. The harvest area shape normally associated with partial cutting with cable yarders is a rectangle with the landing at one corner. Figure 1 from Suddarth and Herrick displays a rectangle constituting the area accessed by a single lateral yarding corridor, divided into two right triangles, and the additive average skidding distance for both triangles is the average skidding distance for the entire area.
The equation described by Suddarth and Herrick is as follows:

\[ Q = (\sqrt{a^2 + b^2} / 3) - [(b^2 / 3a) \ln(\tan((\arctan(b/a)) / 2))] - [(a^2 / 6b) \ln(\tan((\arctan(a/b)) / 2))] \]

Where: \( Q \) = average skidding distance
\( a \) = length of side perpendicular to corridor
\( b \) = length of side parallel to corridor

The authors provide an example to test the accuracy of the formula, and the results demonstrated that average skidding distance was consistently underestimated by 0.04 percent to 0.9 percent.

Peters and Burke (1972) present a simple technique for obtaining area and average yarding distance of a setting with any shape. Their analysis is based on incremental areas and
moments of area. This method is more accurate than Suddarth and Herrick (1964), but is cumbersome, because their technique requires precise three dimensional co-ordinates of an area from maps or a digitizer. Examples and maps are provided.

Bradley (1972) approached average skidding distance using a simple method developed by the Swedish Royal College of Forestry. The method calculates mean straight-line cross-country access distance (average yarding distance), based on desired length, width, and density of proposed roads. Also included is a crude method of correcting skidding distance for broken terrain and non-uniform distributed timber. Examples were not provided.

Donnelly (1978) describes a computational routine for estimating average skidding distance for logging areas with or without irregular boundaries and variable log densities, with a grapple skidder. The model is based on an equation for average yarding distance from Peters and Burke (1972), and has correction factors for slope, and skid trail sinuosity. Results showed that a heavy density of logs located far from the landing significantly increases average yarding distance. Detailed formulation of the model, and an example are provided.

Perkins and Lynn (1979) state that existing methods for calculating average skidding distance provide accurate results for flat surfaces, but are not effective for rough terrain. Similar to the planar approach developed by Peters and Burke (1972), Perkins and Lynn use a 3-dimensional system of planar triangles to simulate undulating topography. An example of this complex method is demonstrated, but fails to simplify the process. The authors show that volume removed per unit area, and average load size are equally important factors in determining the average skidding distance.
Previous methods of estimating logging production have used linear regression techniques based on average skidding distances using the mid-range values of distances. This method is accurate provided logs are uniformly distributed within the harvest area, and a linear relationship exists between regression coefficients and yarding distance (symmetrical). Olsen (1983) presents a method for determining average yarding distance for non-linear terms and for independent variables with non-symmetrical (skewed) distributions. Olsen presents a method of finding the weighted average yarding distance where regression terms are non-linear and distributions nonsymmetrical. A weighted average value was estimated using the Miller and Fruend (1965) integral. Olsen develops formulae for six weighted averages of non-linear terms in regression equations for two types of distributions. Some examples are provided, but the methodology appears awkward.

1.6 Conclusions

Past research has shown that optimal spacing of forest roads, landings, and yarding corridors is a function of fixed and variable operating costs. Optimal spacing was derived by minimising the total cost function with respect to road or corridor spacing and solving for optimum spacing by equating fixed costs and variable operational costs. Much of this information to date on optimal spacing of yarding corridors and roads is derived from studies on clearcut harvesting.

Previous studies on average yarding distances are either founded on, or dispute three basic assumptions: first, that timber is distributed evenly throughout the harvest area, second, that the terrain and harvest area are uniform, and third, that the relationship between yarding productivity
and yarding distance is linear. The researchers then used complicated three dimensional models, or simple two dimensional models based on rectangular or pie-shaped areas to calculate average yarding distances. Unless harvest areas are very small, or the partial cutting silvicultural prescriptions for the harvest area are based on non-uniform small patch clear cutting, the basic assumptions will stand because differences in micro-topography and density of felled and bucked timber will average out over the harvest area. Hence, these cumbersome models (described above) will serve only to complicate regression models associated with yarding distances, and the added accuracy from these yarding distance models is insignificant compared to the variances inherent in regression equations.

It is evident from review of past research that little information is available on the optimal spacing of yarding corridors and few field studies have been conducted on partial cutting with cable harvesting systems in second growth forests of coastal BC. Also, estimates of average yarding distance have been calculated based on the shape of harvest area and topography, and not on operational considerations which dictate the methodology of harvesting, such as rigging configurations, lateral yarding angles, and falling patterns. This study will derive optimal spacing models for yarding corridors in partial cutting by developing total cost equations for typical cable thinning equipment used in coastal BC. The optimal spacing models will be developed by minimizing the total cost equation: first, the cost components of the total cost equation will have to be set as a function of corridor spacing, and the equation differentiated them with respect to spacing. The solution is determined by then solving for spacing. Estimating average yarding distance will be determined using the rectangle method described by Suddarth and Herrick, and
will consider two important factors: the herring bone falling pattern important in partial cutting, and the skyline yarding configurations with drop-line carriages.

2.0 Study Methodology

Study methods are divided into seven sections. The first provides a description of the site selection process and each chosen site is described in terms of site and stand structure, silvicultural prescriptions, and harvesting operations. Second, procedures for harvest layout, design, and engineering for the two field sites are shown. Third, the time study design is presented including a description of the data collection and processing procedures. The fourth section explains the statistical analysis applied to the time study data. Fifth, is a breakdown of the cost analysis methodology. Sixth, the spreadsheet model for predicting partial and clear cutting productivity and costs from statistical analysis and field study observations is presented. Lastly, the optimal skyline spacing model is developed.

2.1 Site Selection and Description

This section is divided into three parts. First, the site selection process is described. Next, each of the selected sites is characterised in terms of tenure, harvesting contractor, physical and topographic attributes, forest stand structure, and silvicultural objectives and treatments. Third, is a detailed description of the forest harvesting operations including equipment, crew, and harvest methods.
2.11 Site Selection

An industry survey was used to identify potential co-operators for field trials. The survey was sent to government officials and forest industry personnel responsible for active logging permits in second-growth forests. Selection from among project sites identified in the survey was done by applying the following criteria:

- partial cutting
- cable yarding systems
- diversity of equipment among sites
- mixture of tenure and ownership among sites

2.12 Site Descriptions and Silvicultural Treatments

Three sites were chosen, but only two were studied. Delays in the scheduled start date for logging prevented inclusion of the third. Site I was a 7-hectare area within the Small Business Enterprise Program Timber Sale License A38818 on Patterson Lake Road near Campbell River. ARTAM Logging of Campbell River won the contract to thin the 65-year-old stand. ARTAM Logging is representative of most independent contractors who generate revenue from harvesting small tracts of timber and selling logs on the open market. ARTAM Logging employs a crew of two to four, and operates a medium-sized swing yarder rigged as a running skyline equipped with a mechanical slackpulling carriage. A small line-skidder is sometimes used to swing logs from the landing. ARTAM contracts independently for log hauling. The field study was conducted October to December, 1992.
Site II was a 6-hectare area within Canadian Forest Products Limited (CANFOR) commercial thinning block CT037. Approximately 20 percent of the area studied was crown land (Tree Farm License 37) and the other 80 percent was freehold land owned by CANFOR. The logging was contracted to Murray Coulter. Coulter has a long-term agreement with CANFOR to harvest a quota of 7000 m³/year. CANFOR pays Coulter a full phase contract rate (stump to dump), however like ARTAM Logging, Coulter contracts independently for trucking of logs. Coulter employs a crew of three and operates a small stationary tower rigged as a standing skyline equipped with a radio-controlled manual slackpulling carriage. The equipment compliment includes a hydraulic heelboom loader used for swinging logs from the landing, road construction, rehabilitation of landings, and occasionally for loading trucks. This study was conducted January to March, 1993.

2.1.21 Site I

The stand at Site I contained a mixture of western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), and red alder (*Alnus rubra*). The canopy was dominated by Douglas-fir and western hemlock, and the understorey was predominantly western red cedar and western hemlock (Table 1). Some dominant and codominant western hemlock trees infected with dwarf mistle-toe (*Arceuthobium tsugense*) had coarse branches, and large sprawling canopies. The terrain was slightly undulating and hummocked, with an average ground slope of 7 percent, and contains areas of poor surface drainage highly susceptible to soil compaction and rutting. Numerous large stumps were present from the previous harvest. Soil texture was a sandy-silt with a rooting depth of at least 1.0 m.
No major water bodies or channels were observed within the block. Wildlife concerns were minimal, although post-harvest conditions were expected to enhance ungulate habitat.

There were two primary objectives for the treatment designed for Site I: (1) to improve stand value by concentrating growth potential on fewer vigorous dominant trees, and (2) to realise intermediate timber volumes by harvesting incipient stand mortality. These objectives were achieved through a combination of low and crown thinning which reduced the stocking from 819 to 300 stems per hectare and removed 30 percent of the original stand volume (Figure 2; Table 1). The planned residual spacing of trees was 5.78 m. Douglas-fir was the preferred residual species, and the majority of trees harvested were western hemlock and western red cedar from codominant, intermediate and suppressed positions in the canopy. Dead and suppressed trees of non-merchantable dimensions were felled. Some smaller, vigorous, western red cedar were left to enhance species diversity. All western hemlock infected with dwarf mistletoe were harvested except if spacing of the residual stand was adversely affected. Western white pine (Pinus monticola) was not harvested.
Table 1. Pre- and Post- Harvest stand conditions for Sites I and II.

<table>
<thead>
<tr>
<th></th>
<th>Site I</th>
<th>Site II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest intensity (%)</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>Residual Stand Spacing (m)</td>
<td>5.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Average piece size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual (m³)</td>
<td>0.32</td>
<td>0.37</td>
</tr>
<tr>
<td>Removed (m³)</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>Average Dbh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual (cm)</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>Removed (cm)</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Average Height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual (m)</td>
<td>26</td>
<td>31</td>
</tr>
<tr>
<td>Harvested (m)</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Basal Area (m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual (m)</td>
<td>35.6</td>
<td>42.75</td>
</tr>
<tr>
<td>Harvested (m)</td>
<td>14.3</td>
<td>25.27</td>
</tr>
<tr>
<td>Volume (m³/ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual</td>
<td>225</td>
<td>534</td>
</tr>
<tr>
<td>Harvested</td>
<td>78</td>
<td>115</td>
</tr>
<tr>
<td>Stems per hectare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-harvest</td>
<td>809</td>
<td>1126</td>
</tr>
<tr>
<td>Post-harvest</td>
<td>304</td>
<td>654</td>
</tr>
</tbody>
</table>
At Site II the stand was dominated by western hemlock, Sitka spruce \((Picea sitchensis)\) and Amabilis fir \((Abies amabilis)\), while the understorey was primarily western hemlock with a small component of Amabilis fir (Figure 3). Some of the dominant western hemlock were infected with dwarf mistletoe. The terrain was hummocked, with an average ground slope of 5 percent. A Class IV stream, too small for fisheries concerns, was located in the western part of the block. Large stumps and snags from the previous harvest and some blowdown were scattered throughout the block. The soil was a fine textured Brunisol of morainal/fluvial parent material, with a rooting depth of 1m and greater. The soil was covered with abundant dead material and
was considered somewhat susceptible to compaction. Great blue herons (*Ardea herodias*) nesting in the area were of concern, so cutting was not permitted within 200 m of the nests.

There were three objectives for the treatment specified for Site II: (1) to improve stand quality, (2) to increase the average stem diameter at rotation age, and (3) to harvest incipient mortality. These objectives were achieved by removing intermediate and suppressed western hemlock and Amabilis fir (low thinning), and crown thinning of dominant and codominant hemlock trees infected with dwarf mistle-toe. All red alder was harvested unless the stem was well formed and vigorous, or an excessively large hole in the canopy was created. Stocking was reduced from 1126 to 654 stems per hectare resulting in the removal of approximately 22 percent of the original stand volume (Table 1). Residual stand spacing was planned for 4.4 m, and Sitka spruce was the preferred residual species. Some large snags were left to enhance wildlife habitat.

![Diameter distribution for residual and harvested trees and snags for Site II.](image)

Figure 3. Diameter distribution for residual and harvested trees and snags for Site II.
2.13 Forest Harvesting Operations and Methods

2.131 Site I

Site I was harvested with a Washington 7840 Swing yarder, configured as a running skyline. Specifications for the yarder are given in Table 2 and the rigging configuration observed on the site is shown in Figure 4a. The Washington 7840 is a medium-sized swing yarder and was equipped with a Young Mechanical Slackpulling carriage controlled by the yarding engineer under voice radio instruction from the hooktender.

The yarding cycle for the swing yarder begins with the yarding engineer spooling the haulback which returns the carriage to the setting. The carriage is then stopped on signal from the hooktender. One mainline line is spooled which feeds it through two sheaves in the mechanical slack-pulling carriage. A third sheave which contains the skidding line is driven by the action of the first two, feeding the skidding line to the hooktender, who pulls it laterally and hooks the next turn. At this point two different events may occur. First, if the hooktender is satisfied that the turn can be pulled into the corridor with little resistance and damage to residual trees, lateral yarding begins with a signal to the yarding engineer. Or, if the hooktender is not satisfied with the presentation of the turn, the yarding engineer is signaled to reposition the carriage until it provides the best lead. After positioning is complete, the turn is yarded laterally. Once the turn has reached the corridor, it is hauled into the landing with the mainline drums. As the turn reaches the landing, the yarder swings, releasing line at the same time, and decks the turn. The chaser, hooktender, or yarding engineer unhooks the turn and the cycle begins again.
Three different crew sizes were observed during the study at Site I. The first was a 2-person crew comprising a yarding engineering who operated the yarder and unhooked logs in the landing, and a hooktender, who set chokers in the woods and gave instructions to the yarding
engineer on carriage placement and operation. The second was a 3-person crew in which a crew member was added to unhook logs at the landing, leaving the yarding engineer to operate the yarder. In the third, a fourth worker operated a skidder used to swing logs from the landing.

The swing yarder observed at Site I has three distinct advantages. First, it can be rigged with a carriage for partial cutting applications, or it can be rigged with a grapple and used for clearcut logging. Second, the mainline and haulback drums can be inter-locked, which allows greater power and control of the cables during yarding. Third, the boom on the swing yarder can swing, which allows better control of the load during yarding and decking. The major disadvantages are its size requirement for extensive space at the landing, and the high cost of ownership. The main advantage of the mechanical slackpulling carriage is that the skidding line is fed mechanically from the carriage, reducing the effort required by the hooktender to pull the skidding line laterally. The disadvantage is that during lateral yarding the carriage is controlled by the yarding engineer, not the hooktender, so control of the turn decreases with distance, due to reduced visibility which can result in increased damage to the residual stand during lateral and corridor yarding.

Harvesting guidelines of the BCMoF for cable thinning within the Campbell River district were in effect for Site I: Yarding corridors had to be located at least 40 m apart, and limited to no more than 2.5 m in width; landings and skyline corridors were to be located in natural openings where possible; limbing and bucking was permitted only in the setting, and whole tree yarding was prohibited; residuals were marked with blue paint by the BCMoF; fines were levied for excessive damage to residual trees (scars larger than 225 cm²), and for harvesting preferred dominants unnecessarily; operations were subject to suspension during times of peak sap flow;
badly damaged trees were to be felled and yarded; utilisation standards specified all logs 3.0 m long with 12.5 cm top diameter and larger had to be yarded; stumps could not exceed 30 cm in height unless they were used to protect residual trees from damage during yarding.

2.132 Site II

Yarding at Site II was done with an Igland Jones Mini-Alp 8000 stationary tower, rigged as a standing skyline and equipped with a radio-controlled, Maki I Manual Slackpulling carriage. Specifications for the yarder are given in Table 2 and the rigging configuration observed at the site is shown in Figure 4b. With this system the mainline cable also serves as the skidding line used during lateral yarding.

The yarding cycle for the Mini-Alp commences with the yarding engineer disengaging the mainline brake and spooling the haulback line. The carriage is pulled by the haulback along the skyline back into the setting (see Figure 4b). The hooktender then stops the carriage by engaging the radio-controlled skyline clamp and pulls the mainline cable through the carriage. The hooktender hooks the turn and signals the engineer to spool the mainline and release the haulback while the carriage is still clamped to the skyline which yards the turn laterally. The hooktender has some freedom to change the position of the carriage during yarding by simply clamping and unclamping it using the radio control. This helps prevent damage to residual trees and reduces turn times by avoiding hang-ups. Once the turn reaches the yarding corridor, the skyline clamp is released, and the turn is hauled into the landing. When the turn reaches the landing the turn is decked, the yarding engineer unhooks the turn and the cycle begins again. Logs decked in the landing were swung from the landing and sorted into piles with a Hitachi hydraulic heelboom loader.
A three-person crew was used throughout the study comprised of a yarding engineer who operated the tower and unhooked logs in the landing, a hooktender who set chokers and controlled the carriage in the woods, and a loader operator.

The stationary yarder observed at Site II has numerous advantages. First, it is small so it does not require wide roads and large landings. Its size also makes it inexpensive to buy and operate. The standing skyline configuration of the Mini-Alp produces better ground clearance than the running skyline. The controls for the yarder are at ground level, affording the yarding engineer easy access for unhooking the turns, especially compared to the swing yarder where the yarding engineer had to climb off the yarder to unhook a turn. Finally, the radio controlled carriage is operated by the hooktender who is in the best position to judge whether turns can be yarded laterally both efficiently and with minimal damage. Disadvantages to the Mini-Alp are its limited payloads due to its small size and its inability to deck logs with the agility of a swing yarder. In addition, the skidding line from Maki I carriage was pulled manually, which creates very arduous work for the hook tender who must pull the line through from the yarder through the carriage, and may have restricted long lateral pulls.

Harvesting operations were subject to CANFOR Limited and BCMoF guidelines, which were as follows; harvestable trees were chosen by the faller, and unlike Site I, residuals trees were not marked; dominant trees were removed only if they were located within the planned yarding corridor, were badly damaged from yarding or falling, were infected with dwarf mistletoe, or were near or already dead; yarding corridors were 3 m or less in width, and spaced at 20 m or more; rub trees were to be utilised for protection of residual stems, especially the larger Sitka spruce; yarding was subject to suspension during peak sap flow if scarring became
problematic; and utilisation standards specified minimum-sized logs with 10 cm top diameter and 3 m length. All logging operations within CANFOR’s TFL is subject to working standards outlined in the TFL 37 Management and Working Plan #6.
Table 2. Equipment and corridor specifications.

<table>
<thead>
<tr>
<th>Yarder</th>
<th>Site 1</th>
<th>Site II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Washington 7840 Swing Yarder</td>
<td>Igland Jones Mini-alp 8000</td>
</tr>
<tr>
<td>Configuration</td>
<td>Running Skyline</td>
<td>Standing Skyline</td>
</tr>
<tr>
<td># of Yarding Drums</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td># of Guyline Drums</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Line Pull (Low gear, empty drum)</td>
<td>16700 kg</td>
<td>4000 kg</td>
</tr>
<tr>
<td>Line speed (empty)</td>
<td>400 m / min</td>
<td>200 m / min</td>
</tr>
<tr>
<td>Horsepower</td>
<td>185 hp</td>
<td>120 hp</td>
</tr>
<tr>
<td>Line Capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skyline</td>
<td>310 m of 19.1 mm cable</td>
<td></td>
</tr>
<tr>
<td>Haulback</td>
<td>950 m of 15.9 mm cable</td>
<td>610 m of 11.1 mm cable</td>
</tr>
<tr>
<td>Mainline(s)</td>
<td>630 m of 15.9 mm cable</td>
<td>310 m of 12.7 mm cable</td>
</tr>
<tr>
<td>Boom Height</td>
<td>13.7 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Corridor specifications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average length</td>
<td>180 m</td>
<td>180 m</td>
</tr>
<tr>
<td>Maximum width</td>
<td>2.5 m</td>
<td>3 m</td>
</tr>
<tr>
<td>Maximum spacing</td>
<td>40 m</td>
<td>25 m</td>
</tr>
<tr>
<td>Carriage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>Young YD</td>
<td>MAKI 1</td>
</tr>
<tr>
<td>Configuration</td>
<td>Mechanical slackpuller</td>
<td>Manual slackpulling</td>
</tr>
<tr>
<td>Radio-controlled</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Weight</td>
<td>205 kg</td>
<td>320 kg</td>
</tr>
<tr>
<td>Max. Lateral Yarding Distance</td>
<td>50m</td>
<td>25m</td>
</tr>
</tbody>
</table>

2.2 Harvest Layout, Engineering, and Preparation of the Sites for Study

Harvest layout, engineering, and preparation of the field sites for study was done in five steps.

1. Preliminary reconnaissance and engineering and logging planning (including primary skyline corridor locations).

2. Tailspar and landing locations.

3. Skyline corridor layout including varying corridor width and loadpath analysis.
4. Rub tree and lateral yarding row locations.

5. Trees marked for measuring yarding distances, and establishment of skyline yarding corridors.

Step 1.

A reconnaissance walk was performed which provided basic information on stand characteristics, terrain and topography, yarding distances, forest stand structure, location of potential tailspar trees and landings, and tailhold and guyline stump anchors. Reconnaissance notes and maps (1:5000 scale) were used to record the following information:

- Possible skyline corridor and lateral yarding row locations.

- Control points such as:
  
  * Locations of tailspar trees and tailhold trees, guyline and tieback stumps.
  * Challenging micro-topography (Rocks, stumps, hummocks, ridges, etc.).
  * Landing locations.
  * Areas of discontinuous forest cover (Rock outcrops, swamps, old cold deck piles from previous logging, old skidding trails, etc.).

- Direction of herring bone felling pattern.

- Forest stand structure including estimates of volume, stand vigour, and tree heights.

Information from the reconnaissance notes was used to formulate a logging and engineering plan (hereafter referred to as the logging plan). The logging plan was in the form of a map which showed proposed tailspar and landing locations, lateral yarding rows (directions), falling direction, and extraordinary areas where logging may have been restricted due to integrated resource management concerns, or topographic and stand structure constraints.
Locating skyline corridors was an iterative process which commenced at the logging plan stage by running bearings between proposed landings and tailspar trees\(^2\). The objective was to develop a parallel network of skyline yarding corridors which minimised yarding costs (optimal spacing between corridors), site degradation and residual tree damage, and met silvicultural and operational guidelines. The distance between skyline yarding corridors was measured directly from the map or calculated using the following formula:

\[
CS = 2[(D \cdot \cos\theta) + (AVE \cdot \cos\theta)] \quad \text{Eq. [12]}
\]

where: 
- \(CS\) = corridor spacing 
- \(D\) = distance of longest lateral pull 
- \(\theta\) = average angle of lead\(^3\) (shown in figure 7) 
- \(AVE\) = Average log length.

If the estimated distance between corridors exceeded the above objectives, or traversed a known trouble area, then a new bearing was attempted. Additional reconnaissance was then required to ground check the corridor locations. If subsequent factors negated the location of a corridor, another bearing was attempted until the network of corridors was located. It should be noted that at both sites the cutblock boundary and haul road locations were already approved, so yarding corridor length was restricted by the approved cutting boundary, and the two-way yarding distance between two adjacent haul roads. In most cases the distance between haul roads was

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\(^2\) In practice corridor spacing is determined by the logging contractor who uses rules of thumb, lacking both the data and knowledge required for completing the appropriate analysis of yarding costs. Both logging contractors spaced their respective corridors as close as possible: ARTAM Logging used a spacing of 40 m and Coulter used 25 m. Both believed that the narrowest spacing would result in the highest economic returns. An objective of the field work of this study was to gain valuable field experience from the logging contractors and crew and to help them better plan and engineer their blocks.

\(^3\) Note: Angle of lead is established by the falling pattern. In partial cutting with cable yarders damage to residual trees is reduced substantially if trees are felled toward the skyline corridor in a "herring-bone" pattern (Kellogg et al. 1986). Preferrably logs should lay at an angle between 30° and 45° to the corridor.
350 m to 500 m, and subsequently skyline corridor lengths were designed roughly at 175 m to 250 m. Uphill yarding is generally more efficient and less destructive than downhill yarding, so skyline corridors with uphill yarding were engineered to be longer wherever possible. When the skyline corridor network was satisfactorily located, tailspar trees and landings were engineered.

**Step 2.**

Landing locations and individual tailspars were chosen after spacing of corridors was determined. Criteria for choosing landings were as follows:

- Natural openings in order to reduce the number of residual trees that would be damaged from decking, swinging logs for loading, guyline clearances, and rigging of guyline stumps.
- Flat areas and benches.
- Availability of adequate guyline stumps.
- Landings positioned to allow access to corridors on high and low sides of haul road.
- Counter weight clearance for swing yarders.
- Adequate distance from special management areas (riparian and wildlife areas).

Individual tailspar trees were then selected from among the candidates for each corridor based on the physical attributes of the trees, and availability of adequate tailhold, guyline, and anchor stumps (if necessary). Size and strength characteristics in rigging applications of second-growth tree species of the Pacific Northwest were discussed by Pyles and Stoupa (1987), Pyles et al. (1988), Pyles et al. (1991), and Sessions et al. (1985). Based on their recommendations, and personal experience of the field staff, the following criteria were used for selecting tailspar and tailhold trees:
• Douglas-fir or hemlock (mistle-toe free)
• Firmly rooted
• Diameter at breast height (dbh) of 50 cm or greater
• Minimum height of 25 m
• No visible fungal infections or other defects

Guyline stumps in the landing and at the tailspar tree, and tieback stumps were chosen using the following guidelines:

• Vertical angle between the ground and the haulback line (angle \( b \) Figure 4a) or the skyline line (angle \( b \) in Figure 4b) should not be greater than 45°

• The lead angle from the tailspar tree to the tailhold tree not offset more than 3° (see Figures 4a, 4b, and 5).

• The angle between the ground and the tailspar guylines should not exceed 45°.

• Guyline stumps should offset from the lead of the skyline at a maximum of 45° horizontal to the tailhold tree (see figure 5).

• Tieback stumps should offset equally from guyline and tailholds and should exceed 45° from lead of the guyline or the skyline (see figure 5)

• If one tieback stump was required, then the angle of lead between the tailhold and the tieback stump should not be offset more than 3° (see figure 5).
Figure 5. Diagram of the relationship between tailspars, tailholds, and tie backs.

**Step 3.**

After a tailspar tree was engineered the skyline corridor was traversed. Profiles were drawn in the field and a crude loadpath and deflection analysis was performed based on principles described in Binkley and Sessions (1978). When deflection was inadequate (ground lead was indicated) either the landing was moved or the tailblock was placed higher in the tailspar. If an excessive quantity of preferred residual trees was located within a proposed corridor, then the bearing would be altered and the corridor re-traversed. In some cases this led to the selection of an alternative tailspar tree.
Step 4.

After the skyline corridors were located, rough locations of lateral yarding corridors were planned and flagged. This was done by walking along each skyline corridor and sighting in to the timber at an angle of approximately 45° to a distance equal to the maximum lateral pull. As with skyline corridors, alleys were sought which did not require cutting of preferred residuals or were well stocked with rub trees. Whenever possible, the intersection of the lateral and skyline corridors was placed such that a rub tree stood on the landing side of the junction.

Step 5.

The final step in preparation of the sites for study was the establishment of corridor boundaries. At Site I, three rectangular corridors were laid-out according to BCMoF specifications stating a maximum width of 2.5 m (see figure 6). Three corridors were laid-out in a wedge-shape to test if the productivity of the swing yarder would improve by providing additional space at the landing. It was hypothesized that wider skyline corridors would make lateral and skyline yarding more productive, because of fewer obstacles, better lateral lead into the skyline corridor, and a better choice of rub trees. It was also hypothesized that the increase in productivity would allow longer lateral pulls, and greater skyline corridor spacing. The wedge-shaped corridors were 1.0 m wide at the tailspar increasing to 4 m at 50 m from the landing, increasing to 8 m at the landing. At Site II, three corridors were laid-out according to the original harvesting guidelines (maximum width 3 m), and three were 6 m wide. The stationary tower is incapable of swinging, so corridors were laid-out in the traditional rectangular shape. Once the final location of a given corridor was determined, yarding distances from the landing were measured and marked on residual or rub trees to permit reading during the time study.
2.3 Time Study Design, Data Collection and Data Processing

A detailed time study was designed for the two harvesting systems using the computer-based system developed by Howard and Gasson (1991). First the work cycle of the two machines was broken down into individual time elements based on published similar studies (Anonymous 1980, Kellogg 1980, Kellogg and Olsen 1984, Kellogg et al. 1986, Mann and Mifflin 1979) and preliminary observation of the two systems. Next, “elemental” variables (Howard and Gasson 1991) which are known to influence elemental times were chosen and techniques for taking field measurements were identified. The time elements and associated elemental variables are given in
Table 3. The work cycle was defined in terms of scheduled machine hours: breaks in the productive work cycle were timed and accounted for in the regression models.
Table 3. Description of time elements and predictor variables.

<table>
<thead>
<tr>
<th>Time Element</th>
<th>Description / Endpoint</th>
<th>Independent Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTHAUL</td>
<td>Begins when the carriage moves away from the yarder, and ends when the hooktender grabs chokers and tong-line from carriage.</td>
<td>DIST</td>
<td>Distance from the landing to the point where lateral yarding commences.</td>
</tr>
<tr>
<td>LATOUT</td>
<td>Begins when the hooktender pulls rigging and tong-line laterally from yarding corridor to logs, and End when the hooktender is in the clear and signals the load to go ahead.</td>
<td>LATDIST</td>
<td>Lateral distance from the yarding corridor to where the turn is hooked.</td>
</tr>
<tr>
<td>HOOK</td>
<td>Begins when rigging drops and hooktender commences to set chokers. Ends when hooktender is in the clear and signals the turn to go ahead.</td>
<td># OF LOGS</td>
<td>Quantity of logs hooked in each turn.</td>
</tr>
<tr>
<td>LATIN</td>
<td>Begins after hooktender has signaled go ahead, and ends when turn arrives at corridor.</td>
<td>LATDIST</td>
<td>Lateral distance from the furthest log hooked to the yarding corridor.</td>
</tr>
<tr>
<td>INHAUL</td>
<td>Begins where the turn enters the yarding corridor and ends when turn is transported to the landing</td>
<td>DIST</td>
<td>After lateral yarding, the distance up the skyline yarding corridor to the landing.</td>
</tr>
<tr>
<td>DECK</td>
<td>Begins when turn enters the landing and ends when the tongline is slackened and the turn is positioned safely on the cold deck pile.</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>UNHOOK</td>
<td>Begins when the chaser unhooks the logs from the chokers, and ends when the chaser is in the clear and the lines tighten in preparation for the next turn.</td>
<td># OF LOGS</td>
<td>Quantity of logs in each turn that arrive at the landing.</td>
</tr>
<tr>
<td>MOVE</td>
<td>Begins when the yarder towers down, and all lines are brought in and blocks are moved to the next corridor, and ends when the yarder is towered up and blocks are hung and the signal to commence yarding has been given.</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>DELAY</td>
<td>Begins when the tower is not performing a task listed above, and ends when normal production resumes.</td>
<td>DELAY CODE</td>
<td>1 = scheduled mechanical 2 = unscheduled mechanical 3 = scheduled personnel 4 = unscheduled personnel 5 = operational</td>
</tr>
</tbody>
</table>

Note: All distance measurements were in metres, and "# OF LOGS" was a numeric quantity.
Site variables were factors that did not vary from turn to turn, such as slope and crew size, but could have influenced the duration of any of the first seven timing elements listed in Table 3. Site variables were identified from past research and preliminary observations of the two harvesting operations. Site variables for the two field sites are listed in Table 4.

Table 4. Description of site variables used for time studies at Site I and II.

<table>
<thead>
<tr>
<th>Site Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>Average slope of terrain profile for the yarding corridor</td>
</tr>
<tr>
<td>Terrain</td>
<td>1 = no more than 1 major obstacle in the skyline corridor</td>
</tr>
<tr>
<td></td>
<td>2 = no more than 3 major obstacles in the skyline corridor</td>
</tr>
<tr>
<td></td>
<td>3 = more than 3 major obstacles in the skyline corridor</td>
</tr>
<tr>
<td># of Chokers</td>
<td>The number of chokers attached to the skidding line</td>
</tr>
<tr>
<td>Crew Size</td>
<td>The number of crew members</td>
</tr>
</tbody>
</table>

Two field technicians were employed in timing the work cycle. First, a timekeeper worked in the woods with the hooktender recording the OUTHAUL, INHAUL, LATOUT, HOOK, LATIN, INHAUL, and DELAYS time elements. The timekeeper estimated outhaul and inhaul distances from distances marked on residual trees, and lateral yarding distances were measured with a tape measure or hip chain. The number of logs hooked during each turn was recorded as chokers were set. The second technician was a "landingperson" who worked around each of the yarders. The landingperson was in radio communication with the timekeeper, and observed the INHAUL, DECK, and UNHOOK time elements. The landingperson observed the number of logs that were unhooked in the landing and communicated this to the timekeeper. The landingperson was also responsible for scaling a sample number of turns for estimation of turn volume. Turn volume was calculated using Smalian's formula. If the hooktender was close to the
landing (<40 m) the landing person would assist in estimating yarding distances. Depending upon the location of a work stoppage (DELAY time element), either or both technicians would record the type of delay.

Handheld computers were used by the timekeeper to measure and store time study data. Site variables listed in table 4 and the weather were observed and stored at the beginning of each shift. Slope was measured with a Sunnto Clinometer, and terrain roughness and crew size and number of chokers was determined visually. If site variables changed, the new values were entered into the computer.

Time study data were uploaded from the handheld computers to a micro-computer daily. Timing data were processed using a series of editing programs developed by Howard and Gasson (1991), which converted the files into a form acceptable for statistical software packages. A log book of daily activities was kept to assist in the processing of the data and the statistical analysis.

2.4 Statistical Analysis of Time Study Data

The time study data were analyzed to determine if significant statistical relationships existed between site variables and time elements for subsequent development of regression models. These regression models are essential for development of production functions and the optimal corridor spacing model. Analysis of the data was divided into three sections: first, the data were stratified in order to test the impact of crew size (Site I) and corridor spacing (Site I and II) on the work cycle. Next, the data were graphed to determine if a linear relationship existed and to eliminate spurious entries. Third, regression analysis tested the relationships
between time elements and site factors (if applicable), between and within strata. The data were
stratified at Site I and Site II in the following manner:

Site I

- Stratum 1: Wide Corridors;
  * Sub-stratum 1: 2-man crew
  * Sub-stratum 2: 4-man crew
- Stratum 2: Narrow Corridors;
  * Sub-stratum 1: 2-man crew
  * Sub-stratum 2: 4-man crew

Site II

- Stratum 1: Wide Corridors;
- Stratum 2: Narrow Corridors;

Following stratification of the data, time elements were plotted against site variables and
the associated predictor variables for each stratum to determine if a linear or curvi-linear
relationship was evident after visual inspection. If a relationship appeared to exist, then regression
analysis was used to determine if the relationship was statistically significant. Then, the time study
data were screened for spurious entries.

Regression analysis of time elements and predictor and site variables was performed to
test for correlation between elemental time data and measured factors described in Tables 3 and 4.
Various functional forms were tried in an attempt to find the best model. If a significant
relationship did not exist between a time element and any of the predictor variables tested, mean
values and other summary statistics were computed. Hypothesis testing was used to test for differences among strata. Data from strata were aggregated if no statistical difference was found. Tukey’s multiple comparison test or Student’s t-test (Freese, 1967; Zar, 1984) were used to determine if the means of times elements not correlated with measured factors differed by strata. The Least Squares Dummy Variable model was used for hypothesis testing among strata on elements for which regression equations were fitted. A sequential approach was used to test the hypotheses of slopes and constants of regression of each element by strata (Anonymous, 1964; Freese, 1967; Zar, 1984). Parallelism, or testing the variation between regression slopes was tested first. If the slopes of two regression lines were significantly different, then regression constants were tested against unique regression lines. If the slopes were not significantly different then coincidental lines were tested against parallel lines. A significance level of 0.05 was used for all hypothesis testing.

2.5 Cost Analysis

A detailed cost analysis was done on both harvesting operations. The logging contractors were interviewed regarding all costs associated with their operations. Specific cost items were classified as either fixed or variable according to standard conventions. Fixed costs were defined as costs that do not vary with production, and include interest, license and insurance, and depreciation. Information on outstanding loans was used when appropriate to compute interest costs. Insurance and licensing fees, where applicable, were standard for the Province. Straight line depreciation was used. Variable costs were defined as those costs which vary in total with
production, and include labour, repair and maintenance, fuel and lubricants, and rigging. Repair and maintenance, fuel and lubricants, and rigging costs were estimated from historical and current machine operating and maintenance records. Labour rates included benefit packages, unemployment insurance (UIC), Workers Compensation, and Canada Pension Plan or other retirement savings plans. Benefit packages, if offered, were standard for the forest industry in BC. Workers Compensation, UIC, and Canada Pension Plan deductions are also standard for workers in BC. The cost data collected by survey were entered into a computer program, PHASE COST CALCULATOR®, which calculates the hourly cost of equipment and labour for individual phases of logging (Howard, 1994).

2.6 Productivity and Costs Comparison of Partial and Clear Cutting

Production functions which account for all time expenditure during the work cycle were created for each yder by summing either the regression equations or means for all of the time elements. The production functions were encoded into a spreadsheet model which was used to predict harvest productivity (m$^3$/hr) and cost ($/m^3$) for both yarders at the two field sites. Production functions were modelled separately for each stratum. Clearcutting was also simulated and compared to the two systems studied. Production equations for clearcutting with the same machines were encoded from published studies done on second-growth stands in the Pacific Northwest of the United States (Aubuchon, 1982).
A deterministic simulation model was used to simulate logging productivity and cost. A spreadsheet model was encoded using the following technique. First, inventory data from the field sites were used to compute the number of trees harvested per hectare, average volume per tree (m³), and the average merchantable height (m) by diameter class, and these values were entered into columns in the spreadsheet. Next the percentage of trees harvested from each diameter class (cruise information) was encoded: for clearcut harvesting all trees were harvested. The average time per turn was calculated by evaluating the production functions encoded in the model. Mean values for the predictor variables taken from the field study were used for the calculations including the number of logs per turn, log length, and corridor and lateral yarding distances. The mean time for the average tree in each diameter class was computed as the product of the mean time per turn and the ratio of the average number of logs per tree and the average number of logs per turn for the class. Yarding productivity was calculated by simply dividing the average volume per tree for each diameter class by the mean turn time per tree. Yarding cost was computed by dividing the cost/hr values from the cost analysis for each harvesting system by the productivity for each diameter class. The average productivity and cost for each site was simply the productivity and cost by diameter class weighted by the number of trees in each class.

The stumpage⁴ allowance for partial cutting under the 1996 Coastal Appraisal Manual was investigated to determine if the cost allowance for partial cutting is comparable to the cost results of this study. The stumpage for partial cutting is calculated by determining the stumpage allowance for clearcutting, plus an additional allowance to account for the higher costs of partial cutting.

⁴ Stumpage is a tax levied by the BC provincial government for timber rights on crown land. Stumpage is based on revenues from harvesting activities with cost allowances deducted for timber development, harvesting, and log transportation.
cutting. The clearcutting allowance includes cost allowances for falling, bucking, yarding, and loading. The following formula\(^5\) was used to estimate stumpage costs cost allowances for clearcutting:

\[
A = 13.6803 + 0.0374(S) \tag{13}
\]

With the following additive formulae for commercial thinning (Eq. 14) and selection logging (Eq. 15) respectively:

\[
A = \frac{VR}{VH + VR} \times [4.52 + 0.0374(S)] \times \frac{VH}{TV} \tag{14}
\]

\[
A = \frac{VR}{VH + VR} \times [6.08 + 0.0374(S)] \times \frac{VH}{TV} \tag{15}
\]

where: \(A = \) Stumpage allowance ($/m^3$).
- \(S = \) Average side slope of cutblock (%).
- \(VR = \) Volume Remaining within the block ($m^3$).
- \(VH = \) Volume Harvested within the block ($m^3$).
- \(TV = \) Total volume under cutting permit ($m^3$).

Results from the cost simulations for the 2-person crew and swing yarder and the stationary yarder logging at Site I was used for comparison purposes. Values for the site parameters were taken from field observations and the silvicultural objectives for Site I, and include the following:

- \(S = 8\%\).
- \(VR = 317 m^3\).
- \(VH = 170 m^3\).
- \(TV = 487 m^3\).

The harvested and residual volume was estimated from the area of the 3 skyline corridors (2.16 ha) and the volume per hectare shown in Table 1. Total volume is the sum of the residual and harvested timber.

\(^5\) From the updated 1996 Coastal Appraisal Manual. BC Ministry of Forests, Victoria, BC.
2.7 Optimal Skyline Corridor Spacing

The purpose of optimum spacing of skyline corridors is to minimise the total cost of skyline yarding. Optimal spacing of yarding corridors can be solved by specifying yarding costs as a function of corridor spacing and minimising with respect to corridor spacing. The total cost function for skyline yarding in this study can be written as,

\[ \text{TYC} = \text{FM} + \text{FY} + \text{CY} + \text{LY} \]  

Where:

- \( \text{TYC} \) = total yarding costs ($/m^3).  
- \( \text{FM} \) = Fixed costs accrued independent of yarding such as engineering, landing construction, delays, and yarder moving and set-up ($/m^3).  
- \( \text{FY} \) = operational costs accrued from unhooking, hooking, decking, and delays independent of corridor spacing and yarding distance ($/m^3).  
- \( \text{CY} \) = operational yarding costs accrued with corridor yarding ($/m^3).  
- \( \text{LY} \) = operational yarding costs accrued with lateral yarding ($/m^3).

Next, appropriate variables in equation [16] are expressed as a function of corridor spacing. Fixed cost per unit volume is simply total fixed costs divided by the total volume harvested from the area serviced by one landing which is the product of external yarding distance, corridor spacing, and the volume per unit area harvested from that area (Figure 7) as shown in equation [17],

\[ \text{FM} = \frac{\text{TFC} \times 10000}{\text{EYD} \times \text{CS} \times \text{V}} \]  

Where:

- \( \text{TFC} \) = the total of all fixed costs accrued from moving from one corridor to the next ($).  
- \( \text{EYD} \) = external skyline corridor yarding distance (m).  
- \( \text{CS} \) = skyline corridor spacing (m).  
- \( \text{V} \) = volume removed per hectare (m$^3$/ha).
Elements of the yarding work cycle which are independent of both yarding distance and lateral yarding distance may be a function of other site or stand factors, but for the purpose of determining optimal corridor spacing, can be totalled and expressed on a per unit cost basis,

\[ FY = \alpha_0 \]  

Eq.[18]

where:

\( \alpha_0 \) = the sum of the costs of elements of the yarding cycle independent of both corridor and lateral yarding distances.

Costs of harvesting in the skyline corridor can be divided into two components: those which are independent of yarding distance, and those that are not.

\[ CY = \alpha_1 + \beta_1 \times AYD \]  

Eq.[19]

where:

\( \alpha_1 \) = cost component of corridor yarding independent of yarding distance (\$/m^3).
\( \beta_1 \) = cost component of corridor yarding (\$/m^3 per metre of yarding distance).
\( AYD \) = average yarding distance along the yarding corridor.

Average corridor yarding distance in rectangular settings is equal to \( EYD/2 \) under the assumption of uniform distribution of timber perpendicular to the skyline corridor (Figure 7).

Values for \( \alpha_1 \) and \( \beta_1 \) can be computed using mean values and regression coefficients from statistical analysis of time study data. Similarly lateral yarding costs can be divided into two components,

\[ LY = \alpha_2 + \beta_2 \times ALYD \]  

Eq.[20]

where:

\( \alpha_2 \) = the cost of lateral yarding independent of lateral yarding distance (\$/m^3).
\( \beta_1 \) = the cost of lateral yarding which is a function of lateral yarding distance (\$/m^3 per meter of lateral yarding distance).

ALYD = average lateral yarding distance (m).

Average lateral yarding distance is equal to one fourth corridor spacing, multiplied by the cosine of the angle between the lateral and skyline corridors, minus a mean log length under the assumption of uniform distribution of timber perpendicular to lateral yarding corridors (distance “c” in Figure 7\(^6\)). Assuming logs are yarded into the corridor from both sides the resultant equation is:

\[
ALYD = \left( \frac{CS}{4 \cdot \cos \theta} - \frac{MLL}{2} \right)
\]

where:

CS = skyline corridor spacing (m).
MLL = mean log length (m).
\( \theta \) = the angle between the lateral yarding corridor and the skyline yarding corridor as shown in Figure 5.

A mean log length is subtracted to account for timber felled from the boundary between two yarding corridors (or 1/2 corridor spacing) towards parallel skyline corridors.

However, felling timber in a herring-bone pattern in lead with lateral yarding corridors is highly recommended (and practised) in both cable and ground-based partial cutting (Angle \( \theta \) in figure 7). This technique helps control damage to residual trees, and increases production by reducing hang-ups and the logs are in lead with the skyline corridor. The computation of average lateral yarding distance must be modified to account for the uneven distribution of timber resulting from this practice. A proportion of the logs within one log length of the corridor can be

\[ c = (a \cdot \cos \theta) - MLL : \text{ where } a = \text{corridor spacing} / 4 \text{ and } MLL = \text{mean log length}. \]

\(^6\) c = (a \cdot \cos \theta) - MLL : where a = corridor spacing / 4 and MLL = mean log length.
hooked directly from the yarding corridor (Figure 7), and will not require lateral yarding. Hence, this proportion must be accounted for in the lateral yarding component of the equation, and in lateral yarding distance. Figure 5 shows that the proportion of area one log length adjacent to both sides of the yarding corridor, in relation to the entire area serviced by one yarding corridor is:

\[
1 - \frac{2 \times MLL \times \cos \theta}{CS}
\]

Eq. [22]

Average lateral yarding distance (ALYD) is the product of equation [21] and [22]:

\[
ALYD = \left(1 - \frac{2 \times MLL \times \cos \theta}{CS}\right) \times \left(\frac{CS}{4 \times \cos \theta} - \frac{MLL}{2}\right)
\]

Eq. [23]

The first part of equation [23] represents the proportion of timber not within one log length of the skyline yarding corridor, all of which will have a lateral yarding distance greater than zero. All timber within one log length of the skyline yarding corridor will have a lateral yarding distance of zero. The average lateral yarding distance is the weighted average of the two. Equation [23] can be simplified to,

\[
ALYD = \frac{CS}{4 \times \cos \theta} + \frac{MLL^2 \times \cos \theta}{CS} - MLL
\]

Eq. [24]

Fixed costs are accrued independently of lateral yarding distance, and must be applied to logs outside of the skyline yarding corridor that are not laterally yarded (shaded area in figure 7). Therefore, applying the weight from equation [18] to the fixed component of lateral yarding, namely the regression constant for lateral yarding yields:
Simplifying equation [25] and substituting equations [25] and [24] into [20] gives the correct expression for lateral yarding costs when timber is felled in a herring-bone pattern,

\[ LY = \alpha_2 - \left( \alpha_2 \cdot \frac{2 \cdot MLL \cdot \cos \theta}{CS} \right) + \beta_2 \cdot \left( \frac{CS}{4 \cdot \cos \theta} + \frac{MLL^2 \cdot \cos \theta}{CS} - MLL \right) \]  

Eq.[26]
Substituting equations [17] - [19] and [26] into equation [16] gives the total cost equation in terms of corridor spacing,

\[
TYC = \left( \frac{TFC \times 10000}{EYD \times CS \times V} \right) + \alpha_0 + \alpha_1 + \beta_1 \times AYD + \alpha_2 - \left( \frac{\alpha_2 \times 2 \times MLL \times \cos\theta \times CS}{CS} \right) + \beta_2 \left( \frac{CS \times MLL^2 \cos\theta}{4 \cos\theta} - MLL \right) \quad \text{Eq.[27]}
\]

To find the optimal corridor spacing, or, the corridor spacing which yields the minimum total yarding costs, equation [27] must be minimised with respect to CS. Differentiating gives,

\[
\frac{\partial TYC}{\partial CS} = - \frac{TFC \times 10000}{EYD \times CS^2 \times V} + \frac{\alpha_2 \times 2 \times MLL \times \cos\theta}{CS^2} + \beta_2 \frac{\beta_2 \times MLL^2 \cos\theta}{4 \cos\theta} \quad \text{Eq.[28]}
\]

Setting equation [28] equal to zero, and solving for corridor spacing gives the equation for optimal corridor spacing,

\[
CS = \left( \frac{40000 \times \cos\theta \times TFC}{EYD \times V \times \beta_2} + 4 \times MLL^2 \times (\cos\theta)^2 - \frac{\alpha_2 \times 8 \times MLL \times \cos\theta^2}{\beta_2} \right)^{1/2} \quad \text{Eq.[29]}
\]

Equation [29] was used to estimate optimal spacing for the two harvesting systems observed in this study. Fixed costs were assumed to include only engineering and yarder moves. Moving costs were calculated as the product of the mean value for the time element MOVE and the cost per hour for the harvesting system. Engineering costs were estimated at two hours of field layout for two people at $25/hr/person based on observations made during the study. The volume per hectare harvested and yarding distances for each site were taken from the study results. The optimal values were then substituted into equation [27], to calculate total yarding cost. Yarding costs at conventional spacing were also calculated by substituting conventional.
spacing observed during the study into equation [27] and compared to costs estimated at the
optimal spacing.

Data used in the models is shown in Tables 1 and 3, the angle of lead for felled timber was 45°,
the minimum log length was 10 m, and the volume per hectare harvested was 78.4 m$^3$/ha and 115
m$^3$/ha for Site I and Site II respectively.

3.0 Results and Discussion

Results from the field trials and development of the optimal skyline corridor spacing model
are presented below. This section is divided into 4 parts. First, the results from the statistical
analysis of the time study data are presented by strata for each element. Second, results from the
cost analysis are shown. Third, production and cost findings from the computer spreadsheet
simulation of harvesting the two sites are presented including a comparison of clearcutting and
partial cutting. Finally, the optimal skyline corridor spacing model is presented, and include a
comparison of costs of optimal spacing and the actual field data values.

3.1 Statistical Analysis

The results from the statistical analysis of the time study data are presented by time
element as they occurred in the work cycle. For each element the functional form of any
regression equations fitted to individual elements is presented, followed by results from hypothesis
testing of either regression models or mean values. The data were broken out by site without
testing differences in machine sizes and rigging methods. For Site I, differences in crew size strata
were tested first, followed by differences in corridor widths. For Site II, hypothesis testing was
performed to differentiate between corridor width strata.

Results from the analysis of OUTHAUL are shown in Table 5. Regression equations were
fitted for OUTHAUL times as a function of yarding distance (DIST). Linear and quadratic
equations were fitted, and linear equations resulted in the best fit. At Site I, the regression
constants for 2-person crews were significantly larger than those for the 3- and 4-person crews.
With the 2-person crew the yarding engineer had to unhook logs in the landing which required
considerable physical effort. Presumably fatigue of the yarding engineer led to reduced
concentration and/or a desire to extend turn times to allow more rest which manifested in longer
OUTHAUL times.

Table 5. Models for estimating OUTHAUL time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>$r^2$</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide 2-person</td>
<td>2</td>
<td>Swing</td>
<td>$T = 0.28717 + 0.003599 \text{DIST}$</td>
<td>0.473</td>
<td>252</td>
<td>0.175</td>
<td>5 - 185</td>
</tr>
<tr>
<td>Wide 3-person</td>
<td>3</td>
<td>Swing</td>
<td>$T = 0.16917 + 0.003599 \text{DIST}$</td>
<td>0.473</td>
<td>252</td>
<td>0.175</td>
<td>5 - 185</td>
</tr>
<tr>
<td>Narrow 2-person</td>
<td>2</td>
<td>Swing</td>
<td>$T = 0.355225 + 0.003714 \text{DIST}$</td>
<td>0.485</td>
<td>324</td>
<td>0.196</td>
<td>1 - 215</td>
</tr>
<tr>
<td>Narrow 4-person</td>
<td>4</td>
<td>Swing</td>
<td>$T = 0.170249 + 0.003714 \text{DIST}$</td>
<td>0.485</td>
<td>324</td>
<td>0.196</td>
<td>1 - 215</td>
</tr>
<tr>
<td>Both 3-person</td>
<td>3</td>
<td>Stationary</td>
<td>$T = 0.136633 + 0.005082 \text{DIST}$</td>
<td>0.741</td>
<td>587</td>
<td>0.115</td>
<td>14 - 198</td>
</tr>
</tbody>
</table>

The coefficient fitted to outhaul distance for the 2-person crew was significantly smaller
for wide corridors than narrow corridors. Wider corridors allowed faster OUTHAUL times for a
number of reasons. First, the yarding engineer had more room in the landing in which to
manoeuvre the boom of the swing yarder and more freedom to return the carriage unimpeded to the setting. The yarding engineer also had a better line of site in wide corridors from the landing up into the corridor and was able to stop the carriage closer to the hooktender, eliminating unnecessary carriage positioning before the LATOUT element. Finally, more room in the landing allowed smoother decking of logs and decreased the height of log decks easing the task of unhooking and decreasing fatigue for the yarding engineer. For Site II, hypothesis testing showed no significant differences between the regression equations for wide and narrow corridors, so the data were pooled.

Regression equations were fitted for LATOUT to predict the time per turn as a function of lateral yarding distance (see Table 6). No significant correlation was found with any of the other variables. Hypothesis testing showed that the regression coefficient fitted to LATDIST was smaller for the 4-person crew than the 2-person crew in narrow corridors. There is no clear explanation as to why crew size would influence LATOUT time, because the extra crew members were located at the landing and not in the setting where LATOUT occurs, so perhaps these results are spurious. There was no significant difference between regression equations fitted to LATOUT time for 2- and 3-person crews in wide corridors, so the data were pooled.

Table 6. Models for estimating LATOUT time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>$r^2$</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide 2 &amp; 3</td>
<td>Swing</td>
<td>$T = 0.348626 + 0.026701$ LATDIST</td>
<td>0.278</td>
<td>312</td>
<td>0.266</td>
<td>1 - 34</td>
<td></td>
</tr>
<tr>
<td>Narrow 2</td>
<td>Swing</td>
<td>$T = 0.378003 + 0.032705$ LATDIST</td>
<td>0.311</td>
<td>442</td>
<td>0.28</td>
<td>1 - 34</td>
<td></td>
</tr>
<tr>
<td>Narrow 4</td>
<td>Swing</td>
<td>$T = 0.378003 + 0.021447$ LATDIST</td>
<td>0.311</td>
<td>442</td>
<td>0.28</td>
<td>1 - 34</td>
<td></td>
</tr>
<tr>
<td>Both 3</td>
<td>Stationary</td>
<td>$T = 0.348549 + 0.049499$ LATDIST</td>
<td>0.325</td>
<td>670</td>
<td>0.329</td>
<td>1 - 25</td>
<td></td>
</tr>
</tbody>
</table>
The LATOUT regression coefficients for the 2-person crew in wide corridors were significantly smaller than in narrow corridors at Site I. Lower LATOUT time in wide corridors resulted from two factors. First, wider corridors provided more options for the hooktender when pulling the skidding line from the carriage to the setting, allowing the worker to take the path of least resistance from the corridor to the logs. Second, more logs were felled in the clearcut skyline corridor for the wide corridors, so a higher proportion of the timber could be reached without regard for residual trees. There was no significant difference between the equations fitted to LATOUT for wide and narrow corridors at Site II, so the data were pooled.

The results for the regression analysis of HOOK are shown in Table 7. The number of logs hooked (# OF LOGS) was the only variable correlated with HOOK time, and the linear model had the best fit. The coefficient fitted to # OF LOGS for the 4-person crew was significantly smaller than the 2-person crew at Site I. It is difficult to speculate as to why an increase in crew size would decrease HOOK time, because the hooktender worked independent of the extra crew members in the landing. However, different hooktenders set chokers in the two crews, so perhaps the differences observed were due to human factors. There was no significant difference found between the equations fitted to HOOK times for 2- and 3-person crews in wide corridors so the data were pooled.

Table 7. Models for estimating HOOK time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>( r^2 )</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (logs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>2&amp;3</td>
<td>Swing</td>
<td>( T=0.441278+0.362685 ) # OF LOGS</td>
<td>0.308</td>
<td>311</td>
<td>0.715</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Narrow</td>
<td>2</td>
<td>Swing</td>
<td>( T=0.343127+0.496882 ) # OF LOGS</td>
<td>0.49</td>
<td>494</td>
<td>0.638</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Narrow</td>
<td>4</td>
<td>Swing</td>
<td>( T=0.343127+0.273395 ) # OF LOGS</td>
<td>0.49</td>
<td>494</td>
<td>0.638</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Wide</td>
<td>3</td>
<td>Stationary</td>
<td>( T=0.226307+0.22322 ) # OF LOGS</td>
<td>0.302</td>
<td>687</td>
<td>0.372</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Narrow</td>
<td>3</td>
<td>Stationary</td>
<td>( T=0.331289+0.22322 ) # OF LOGS</td>
<td>0.302</td>
<td>687</td>
<td>0.372</td>
<td>1 - 5</td>
</tr>
</tbody>
</table>
The constant in the equation fitted to HOOK times was significantly smaller for narrow corridors than wide with 2-person crews, but the coefficient fitted to # OF LOGS was significantly smaller for wide corridors than narrow for Site I. One possible explanation for this finding is that in wide corridors where more logs were concentrated in the clearcut area, the hooktender took more time to plan turns prior to hooking (larger constant), but walking to logs and attaching chokers was faster (smaller coefficient on # OF LOGS) because of advanced planning and the logs being closer together. The same hooktender hooked logs for the 2-person crew in narrow and wide corridors.

The regression constant fitted to the equation for HOOK time was significantly smaller for wide than narrow corridors at Site II which is the opposite finding from Site I. Presumably human factors contribute to the difference where with the stationary yarder apparently the hooktender required less time for ‘planning’ turns when logs were more concentrated (wide corridors), but the same amount of time per log to attach the choker.

Results from the regression analysis for LATIN are in Table 8. Regression analysis of LATIN time per turn showed lateral yarding distance (LATDIST) was the only variable correlated, and the linear model gave the highest coefficient of determination ($r^2$). Hypothesis testing showed that the constant for the 4-person crew in narrow corridors was significantly smaller than that fitted for the 2-person crew. Again, the only explanation is the different hooktenders. Crew size had no impact on LATIN times in wide corridors at Site I, so the data were pooled.
Table 8. Models for estimating LATIN time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>( r^2 )</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>2 &amp; 3</td>
<td>Swing</td>
<td>( T = 0.414084 + 0.014665 \text{LATDIST} )</td>
<td>0.11</td>
<td>283</td>
<td>0.271</td>
<td>1 - 36</td>
</tr>
<tr>
<td>Narrow</td>
<td>2</td>
<td>Swing</td>
<td>( T = 0.422861 + 0.01668 \text{LATDIST} )</td>
<td>0.221</td>
<td>361</td>
<td>0.233</td>
<td>1 - 34</td>
</tr>
<tr>
<td>Narrow</td>
<td>4</td>
<td>Swing</td>
<td>( T = 0.284902 + 0.01668 \text{LATDIST} )</td>
<td>0.221</td>
<td>361</td>
<td>0.233</td>
<td>1 - 34</td>
</tr>
<tr>
<td>Both</td>
<td>3</td>
<td>Stationary</td>
<td>( T = 0.192788 + 0.025779 \text{LATDIST} )</td>
<td>0.346</td>
<td>645</td>
<td>0.155</td>
<td>1 - 25</td>
</tr>
</tbody>
</table>

Both the constants and the coefficients fitted for LATIN were smaller for wide corridors than narrow with 2-person crews. There are many factors inhibiting lateral yarding including obstacles such as residual stems, rocks, stumps, other logs, and operational problems like the positioning of the carriage, poor deflection, and the angle of the turn. More room in the corridor allows the hooktender to swing the turn into favourable lead with greater ease, reducing the risk of damage to residuals and minimising the influence of the factors mentioned above. Also, the wedge shaped corridors allowed the yarding engineer to “swing” the yarder, permitting adjustment of the position of the lines and the carriage during lateral yarding, which resulted in a more favourable lead for the turn entering the corridor. The regression models for LATIN were not significantly different for wide and narrow corridors at Site II so the data were pooled.

Inhaul distance (DIST) was the only site factor that was significantly correlated with INHAUL time, and the linear model provided the best fit. Regression equations and results for INHAUL are in Table 9. Hypothesis testing showed that the constant for the equation fitted to INHAUL time for the 4-person crew was significantly smaller than the coefficient for the 2-person crew in narrow corridors. The 4-person crew had two distinct advantages in decreasing INHAUL times. First, the landing was continually cleared of logs by the skidder so the yarding
engineer did not have to reduce line speeds near the landing in order to prepare for the decking of logs. Second, the yarding engineer was not responsible for unhooking turns so fatigue was less of a factor. Crew size had no impact on wide corridors at Site I so the data were pooled. The regression model fitted for the 4-person crew in narrow corridors had the shortest observed times for INHAUL of all crews at Site I.

Table 9. Models for estimating INHAUL time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>( r^2 )</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide 2 &amp; 3</td>
<td>Swing</td>
<td>( T=0.241494+0.004994 \text{ DIST} )</td>
<td>0.639</td>
<td>255</td>
<td>0.173</td>
<td>5 - 180</td>
<td></td>
</tr>
<tr>
<td>Narrow 2</td>
<td>Swing</td>
<td>( T=0.19126+0.006843 \text{ DIST} )</td>
<td>0.678</td>
<td>314</td>
<td>0.252</td>
<td>1 - 212</td>
<td></td>
</tr>
<tr>
<td>Narrow 4</td>
<td>Swing</td>
<td>( T=0.049739+0.006843 \text{ DIST} )</td>
<td>0.678</td>
<td>314</td>
<td>0.252</td>
<td>1 - 212</td>
<td></td>
</tr>
<tr>
<td>Wide 3</td>
<td>Stationary</td>
<td>( T=0.181258+0.004758 \text{ DIST} )</td>
<td>0.763</td>
<td>784</td>
<td>0.187</td>
<td>2 - 198</td>
<td></td>
</tr>
<tr>
<td>Narrow 3</td>
<td>Stationary</td>
<td>( T=0.181258+0.005815 \text{ DIST} )</td>
<td>0.763</td>
<td>784</td>
<td>0.187</td>
<td>2 - 198</td>
<td></td>
</tr>
</tbody>
</table>

Hypothesis testing showed that the constant for the 2-person crew in narrow corridors was significantly smaller than wide corridors at Site I, and the coefficient fitted for DIST was smaller for the 2-person crew in wide corridors than narrow. The regression lines for the models intersect at an inhaul distance of 27 m (DIST): narrow corridors have shorter INHAUL times from 0 - 27 m, and wide corridors have shorter inhaul times for distances greater than 27 m. Apparently yarding distances up to 27 m provide no advantage to the wide, wedge-shaped corridors, however as yarding distances increase, the extra room and visibility becomes beneficial and the effect on INHAUL time is finally realised.

The coefficient fitted for DIST was significantly smaller for wide corridors when compared to narrow corridors at Site II. The additional space provided by wider corridors reduced the chances of the turns hitting residual trees at the corridor edges and increased visibility for the yarder engineer, thus permitting higher line speeds and faster travel times.
Results from the analysis of deck time are found in Table 10. No site variables were found to be significantly correlated with DECK time. Mean DECK time per turn was not significantly different for 2- and 3 person crews in wide corridors, and 2-person crews in narrow corridors. The data were pooled for these strata and a single mean computed. Mean decking time per turn for the 4-person crew was significantly smaller than all other crew sizes. DECK times for the pooled data where logs were not swung from the landing took on average 323 percent longer than when logs were swung. When logs were swung from the landing there was no need to pile logs neatly to conserve space so decking was faster. There was no difference in decking time between narrow and wide corridors at Site II. The stationary tower can not swing so logs were decked exactly the same, independent of corridor width.

Table 10. Models for estimating DECK time (min) per turn

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Std. Dev.</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>2</td>
<td>Swing</td>
<td>0.577</td>
<td>0.093</td>
<td>1.89</td>
<td>0.405</td>
<td>264</td>
</tr>
<tr>
<td>Wide</td>
<td>3</td>
<td>Swing</td>
<td>0.442</td>
<td>0.083</td>
<td>1.8</td>
<td>0.334</td>
<td>117</td>
</tr>
<tr>
<td>Narrow</td>
<td>4</td>
<td>Swing</td>
<td>0.1744</td>
<td>0.059</td>
<td>1.967</td>
<td>0.136</td>
<td>141</td>
</tr>
<tr>
<td>Narrow</td>
<td>2</td>
<td>Swing</td>
<td>0.574</td>
<td>0.016</td>
<td>1.967</td>
<td>0.379</td>
<td>222</td>
</tr>
<tr>
<td>Both</td>
<td>3</td>
<td>Stationary</td>
<td>0.4531</td>
<td>0.017</td>
<td>2.633</td>
<td>0.559</td>
<td>641</td>
</tr>
</tbody>
</table>

Results from the regression analysis of UNHOOK are shown in Table 11. UNHOOK time per turn were found to be correlated only with the number of logs unhooked, and the linear model gave the highest coefficient of determination. The regression constant for the 4-person crew was significantly smaller than the 2-person crew in narrow corridors at Site I. The combination of swinging with the skidder and unhooking by a chaser contributed to shorter unhook time per turn for the 4-person crew. The skidder operator in the 4-person crew kept the landing clear of logs, improving working conditions for the chaser. The chaser also contributed to a safer, more
efficient work environment by removing hazardous brush and debris from the landing, deliming and bucking some logs to sawmill standards, and ensuring logs were placed perpendicular to the corridor so that the incoming turn could be located for easy access to chokers for unhooking logs from the yarder and re-setting of chokers for the skidder. The 3-person crew at Site I also employed a chaser, but did not have a skidder to swing the logs. The results showed that there was no difference between the yarding engineer and the chaser unhooking the logs in 2-person and 3-person respectively. The majority of time spent unhooking logs was observed to involve climbing log piles and attempting to unhook chokers, and not in getting from the yarder to the log pile.

Table 11. Models for estimating UNHOOK time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of Yarder</th>
<th>Model</th>
<th>$r^2$</th>
<th>Sample Size</th>
<th>Std Error</th>
<th>Range (logs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>2 &amp; 3</td>
<td>Swing</td>
<td>$T=0.282672+0.094265$ (# of logs)</td>
<td>0.238</td>
<td>188</td>
<td>0.2366</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Narrow</td>
<td>2</td>
<td>Swing</td>
<td>$T=0.4761+0.096496$ (# of logs)</td>
<td>0.2</td>
<td>317</td>
<td>0.31</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Narrow</td>
<td>4</td>
<td>Swing</td>
<td>$T=0.230834+0.096496$ (# of logs)</td>
<td>0.2</td>
<td>317</td>
<td>0.31</td>
<td>1 - 6</td>
</tr>
<tr>
<td>Both</td>
<td>3</td>
<td>Stationary</td>
<td>$T=0.548535+0.125742$ (# of logs)</td>
<td>0.054</td>
<td>612</td>
<td>0.429</td>
<td>1 - 5</td>
</tr>
</tbody>
</table>

Results from hypothesis testing on UNHOOK time showed that the 2-person crew in wide corridors had a significantly smaller regression constant than the 2-person crew in narrow corridors at Site I. Wide, wedge-shaped corridors permit the yarding engineer to swing turns and deck the logs carefully, in wider and lower decks. This resulted in shorter unhook times because the chokers were more accessible for unhooking, and the log decks were less difficult to climb. The combination of these factors decreased unhooking time per turn in wider corridors by an average 45 percent when compared to unhook times in narrow corridors.
Regression analysis was not performed for the MOVE time element. MOVE is the non-productive time spent de-rigging the skyline, guylines, tiebacks, blocks and equipment, and moving it to the next corridor. Very few moves occurred at either site during the study, so statistical comparison was not practical. Summary statistics from analysis of Move are shown in Table 12.

Table 12. Models for estimating MOVE time (min) per turn.

<table>
<thead>
<tr>
<th>Crew Size</th>
<th>Type of yarder</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Std. Dev.</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Swing</td>
<td>0.70064</td>
<td>0</td>
<td>94</td>
<td>6.667</td>
<td>512</td>
</tr>
<tr>
<td>3</td>
<td>Stationary</td>
<td>0.90812</td>
<td>0</td>
<td>138.806</td>
<td>8.688</td>
<td>647</td>
</tr>
</tbody>
</table>

The swing yarder was relatively fast to de-rig, because it has a simple rigging configuration, and only used two guylines to support the yarder, and two to support the tailspar. To speed up tailspar rigging and de-rigging, the swing yarder crew used a ladder to hang the tail blocks and tie guy lines. However, the ladder restricted the height of tailspar blocks to 5 m, which in the flat, undulating terrain at Site I led to groundleading. The crew was not overly concerned about this, because of the power of the swing yarder.

The stationary yarder has a more complicated rigging configuration than the swing yarder, so set-up required more time. The crew for the stationary yarder climbed the tailspar to hang tailspar blocks and tie guy lines, which took longer than the method used by the crew at Site I. However, the crew at Site II was able to hang tailspar blocks 10 m and higher in the tailspar, and did not experience deflection problems like those observed at Site I. For the stationary yarder a corner block for the haulback line was hung in a tree near the landing to ensure that the haulback was clear of the ground during yarding, which prevented tangling with the mainline and the load. The stationary yarder used at least three guylines for both the tower and the tailspar.
Delays in production were not attributable to any one site factor, but resulted from an unscheduled activity that required yarding to stop. Mean DELAY times per turn were calculated, and hypothesis testing performed. Sample statistics are shown in Table 13. There was no significant differences in mean DELAY time between any strata at Site I or Site II.

Table 13. Models for estimating DELAY time (min) per turn.

<table>
<thead>
<tr>
<th>Corridor Width</th>
<th>Crew Size</th>
<th>Type of yder</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>Std. Dev.</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both</td>
<td>All</td>
<td>Swing</td>
<td>0.9513</td>
<td>0</td>
<td>22.409</td>
<td>2.3</td>
<td>522</td>
</tr>
<tr>
<td>Both</td>
<td>3</td>
<td>Stationary</td>
<td>0.81783</td>
<td>0</td>
<td>10.657</td>
<td>1.15625</td>
<td>647</td>
</tr>
</tbody>
</table>

3.2 Production Functions

In this section production functions for each strata are presented, and their use is demonstrated with an example. The general form of the production functions is:

Total Time = OUTHAUL + LATOUT + HOOK + LATIN

+ INHAUL + DECK + UNHOOK + MOVE + DELAY

Eq.[30]

The following production functions for each strata were developed by summing the constant values from the regression equations and mean times for elements not fitted to any site or stand variables, and summing the coefficients for like explanatory variables.

*Swing yader harvesting in narrow corridors with a 2-person crew*

TIME=4.720816+0.010553DIST+0.049385LATDIST+0.593378# OF LOGS  Eq.[31]

*Swing yader harvesting in narrow corridors with 4-person crew*

TIME=3.183894+0.010553DIST+0.038127LATDIST+0.369891# OF LOGS  Eq.[32]

*Swing yader harvesting in wide corridors with 2-person crew*

TIME=4.01528+0.008593DIST+0.041523LATDIST+0.45695# OF LOGS  Eq.[33]
Swing yarder harvesting in wide corridors with 3-person crew

\[ \text{TIME} = 3.76228 + 0.008593 \times \text{DIST} + 0.041523 \times \text{LATDIST} + 0.45695 \times \text{# OF LOGS} \]  
Eq. [34]

Stationary tower harvesting in narrow corridors with 3-person crew

\[ \text{TIME} = 3.81316 + 0.010897 \times \text{DIST} + 0.075278 \times \text{LATDIST} + 0.348962 \times \text{# OF LOGS} \]  
Eq. [35]

Stationary tower harvesting in wide corridors with 3-person crew

\[ \text{TIME} = 3.918142 + 0.00984 \times \text{DIST} + 0.075278 \times \text{LATDIST} + 0.075278 \times \text{# OF LOGS} \]  
Eq. [36]

The example below demonstrates the computation of total cycle time, turns per hour, and \( m^3/hr \) using two of the production functions shown in Table 14. The example compares the 2-person crew in narrow corridors at Site I to the 3-person crew at Site II.

Table 14. Estimating harvest system productivity from production functions.

Step 1: choose the appropriate production functions.

*Swing yarder, 2-person crew, narrow corridors*

\[ \text{min/turn} = 4.720816 + 0.010553 \times \text{DIST} + 0.049385 \times \text{LATDIST} + 0.593378 \times \text{# OF LOGS} \]

*Stationary yarder, 3-person crew, narrow corridors*

\[ \text{min/turn} = 3.81316 + 0.010897 \times \text{DIST} + 0.075278 \times \text{LATDIST} + 0.348962 \times \text{# OF LOGS} \]

Step 2: find the stand and site variables needed to evaluate the equations

- Average yarding distance: 100 m
- Average lateral yarding distance: 10 m
- Average # of logs per turn: 2.7
- Average volume/log: 0.33 \( m^3 \)
Step 3: compute the mean time per turn

\[ 5.7 \text{ min/turn} = 4.720816 + 0.010553 (100) + 0.049385 (10) + 0.593378 (2.7) \]

\[ 6.6 \text{ min/turn} = 3.81316 + 0.010897 (100) + 0.075278 (10) + 0.348962 (2.7) \]

Step 4: compute logging productivity by converting to hours and multiplying by the volume per turn.

\[ 9.45 \text{ m}^3/\text{hr} = \frac{60 \text{ min/hr}}{5.7 \text{ min/turn}} \times (2.7 \text{ logs/turn} \times 0.33 \text{ m}^3/\text{log}) \]

\[ 8.20 \text{ m}^3/\text{hr} = \frac{60 \text{ min/hr}}{6.6 \text{ min/turn}} \times (2.7 \text{ logs/turn} \times 0.33 \text{ m}^3/\text{log}) \]

3.3 Cost Analysis

Analysis of hourly costs was done by harvesting system at Site I and Site II, and broken down further by crew size at Site I. The results from the cost analysis are shown in Table 15.

At Site I the largest proportion of fixed costs was depreciation which represented 14 percent, 12 percent, and 9 percent of total hourly costs for the 2-, 3-, and 4-person crews respectively. Equipment operating costs comprised 16 percent, 13 percent, and 13 percent of total costs for the three crew size, which was higher than normal according to the contractor due to unusually expensive repairs in recent years. Labour costs constituted the largest proportion of total costs at 56 percent, 64 percent, and 70 percent for the three crew sizes. The 3-person crew at Site I operated with the identical equipment as the 2-person crew, hence equipment costs remained the same. However, labour costs increased by $24.19/hr or nearly 23 percent. The 4-person crew at Site I had two additional workers and a skidder compared to the 2-person crew. Fixed equipment costs did not increase because the skidder was fully depreciated and paid for. Equipment operating costs increased by $4.79/hr or 28 percent. Total costs for the 4-person crew were 55 percent higher than the 2-person crew.
Table 15. Hourly costs for the Two Harvesting Systems

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Site / Crew Size</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site I 2</td>
<td>3</td>
<td>4</td>
<td>Site II 2.5</td>
</tr>
<tr>
<td><strong>Equipment Fixed Costs</strong></td>
<td>License &amp; Insurance</td>
<td>10.13</td>
<td>10.13</td>
<td>10.13</td>
</tr>
<tr>
<td></td>
<td>Depreciation</td>
<td>14.92</td>
<td>14.92</td>
<td>14.92</td>
</tr>
<tr>
<td></td>
<td>Interest (loans)</td>
<td>4.04</td>
<td>4.04</td>
<td>4.04</td>
</tr>
<tr>
<td><strong>Variable Costs</strong></td>
<td>Equipment Operating</td>
<td>16.95</td>
<td>16.95</td>
<td>21.74</td>
</tr>
<tr>
<td></td>
<td>Labor</td>
<td>59.24</td>
<td>83.43</td>
<td>111.97</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td>105.28</td>
<td>129.47</td>
<td>162.80</td>
</tr>
</tbody>
</table>

At Site II the stationary yarder was operating within TFL and private land, so licensing and insurance requirements were different than for the swing yarder which was operated on public land. The stationary yarder was not required to have licensing, and according to the contractor none of his equipment was insured. As a result fixed equipment costs in total represented only 9 percent of total costs. Like the harvesting system at Site I, system costs were dominated by labour which represented 71 percent of the total. The harvesting system at Site II was 37 percent, 41 percent, and 53 percent cheaper than the 2-, 3-, and 4-person crews at Site I respectively.

3.4 Productivity and Costs of Partial and Clearcut Logging.

The results from the simulation of logging production at Site I are shown in Figure 8. Production with the swing yarder was highest with the 4-person crews in narrow corridors. These findings are consistent with Burrows et al. (1986), Kellogg (1981), and Kellogg and Olsen
(1984) who found that cable yarder productivity in partial cutting was higher when logs were swung from the landing with a skidder. The 4-person crew had the shortest time for decking and unhooking, because landings were kept clear at all times. Another factor which contributed to higher production was that log loading did not interfere with yarding operations. The 3-person crew had the highest productivity in wide corridors. The 3- and 4-person crews had a chaser unhooking turns, while the yarding engineer was required to unhook turns in the 2-person crews. Aulerich et al. (1974), and Jones et al. (1972) also found that productivity increased with larger crew sizes, and that the chaser and skidder operators had the highest productive working time (81 percent) of all crew members.

Figure 8. Simulated Logging Productivity Site I. (Average yarding distance 90 m, average lateral yarding distance 10 m, average number of logs 2.7)

At Site I the productivity of the swing yarde was 16 percent higher and the stationary yarde was 2 percent higher in wide corridors compared to narrow. Increased productivity from
the swing yarder in wide corridors can be attributed to the following factors. First, the extra
room allowed the yarding engineer to manoeuvre turns around obstacles preventing hangups and
speeding turn times. Second, wider corridors provided the hooktender with more options in
which to build turns that would break-out faster from the setting and with less concern for
damage to residual trees. Finally, the swing yarder was able to build shorter, wider log decks in
the landing, which sped unhooking of logs. Simulations at Site I demonstrated that corridor
width had little impact on the productivity of the stationary yarder.

Results from the simulations of logging production for Site II are shown in Figure 9.
Productivity was higher for both machines and all crew sizes compared to Site I, and the findings
regarding the influence of crews size on productivity were similar. Larger average piece size at
Site II led to higher productivity, which concurs with studies by Ashe (1916), Lyford (1934), and
Mann and Mifflin (1979) who showed that piece size was the major consideration when
comparing partial cutting operations at different sites.
Production simulations at Site II showed that swing yarder productivity increased by 10 percent and stationary yarder productivity increased by 6 percent in wide corridors compared to narrow. The average lateral yarding distance at Site II was half as long as Site I, because thinning intensity was lower, log lengths were longer, piece size was larger and corridor spacing was narrower (Table 1). The stationary yarder benefited more from wider corridors at Site II than at Site I. This is attributable to shorter lateral yarding distances. Many studies have shown that productivity of small yarders varies greatly with increasing lateral yarding distances (Burrows et al., 1986; Hochrien and Kellogg, 1988; Kellogg, 1981; Kellogg and Olsen, 1984; Kellogg et al., 1986; Mann and Mifflin, 1979; Peter and Kellogg, 1980; and Samset, 1990).

Clearcutting was the most productive method of harvesting at both sites. Clearcutting with the swing yarder rigged with the grapple was at least 370 percent more productive than
partial cutting, and the stationary yarder was at least 250 percent more productive in clearcutting. In similar studies, Dykstra (1976) found that clearcutting with a swing yarder rigged with a grapple was substantially more productive than the same machine operating in partial cuts rigged with a mechanical slack pulling carriage, and Mann and Mifflin (1979) found that a small stationary yarder was 200 percent more productive in clearcutting than partial cutting.

Clearcut harvesting out-produced partial cutting harvesting for three fundamental reasons. First, workers and machinery do not have to manoeuvre around residual trees which speeds turn times. Second, more volume is removed per hectare accessed by a setting which means there is less productive time lost to moving and set-up of equipment per unit volume harvested. Third, with a grapple carriage, hook time is substantially shorter than when chokers are set by hand. Although the number of logs per turn may be lower, the net affect is higher production. When chokers are set in stationary yarder settings, larger turns can be built compared to partial cutting because there is more felled timber closer together and less care and attention is required because damage to residual trees does not occur, so production is higher.

The stumpage allowance for clearcutting Site I was calculated at 13.80 $/m^3. A recent cost survey\(^7\) for coastal logging operations showed that average 1994 costs for falling and bucking, yarding, and loading were 18.15 $/m^3, where yarding costs constituted 56 percent (10.16 $/m^3) of the total cost. Fifty-six percent of the stumpage allowance is 7.73 $/m^3, which is slightly higher than the yarding costs of the stationary yarder (6.82 $/m^3) and substantially higher than the swing yarder (4.32 $/m^3). The additional cost for commercial thinning and selection logging was calculated at 1.10 $/m^3 and 1.45 $/m^3, respectively. The differences in yarding costs between

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clearcutting and partial cutting for the swing and stationary yarder in narrow corridors were 14.64 $/m^3$ and 10.96 $/m^3$, respectively, which is far greater than the additive allowances shown above. In addition, the additive allowances are designed to account for difficulties involved in falling and bucking, yarding, and loading, and the cost of these components was not included in the comparison, therefore our analysis is conservative.

The results from the simulations of logging cost for Site I are shown in Figure 10. The least costly system of partial cutting at Site I was the stationary yarder in wide corridors. For the swing yarder, the 2-person crew working in wide corridors was the least expensive, while the most costly was the 4-person crew in narrow corridors. The 4-person crew had the highest production, but productivity gains from the extra personnel and equipment were not offset by increased costs from the added equipment and labour. It was cheaper for both the swing yarder and the stationary yarder to operate in wide corridors than narrow corridors at Site I. Yarding costs were 14 percent lower in wide corridors compared to narrow for the swing yarder, and 6 percent lower for the stationary machine.
Figure 10. Simulated unit cost for Site I. Average yarding distance of 90 m, average lateral yarding of 10 m, and average number of logs hooked was 2.7.

Results from the simulations of yarding costs for Site II are shown in Figure 11. The relationship between costs and crew size were similar to those for Site I. Costs for all crew sizes were lower at Site II compared to Site I, because harvesting at Site II was concentrated in larger diameter classes (Figure 2), resulting in larger average piece size and lower per unit volume costs. Clearcutting was about one third the cost of partial cutting.
3.5 Optimal Yarding Corridor Spacing

Results from the optimal spacing analysis are shown in Table 16. The 2-person crew working in wide corridors at Site I demonstrated the widest optimal spacing and the lowest cost. This system had the lowest variable lateral yarding costs ($\beta_2$ values) which explains why optimal spacing was the widest. The 4-person crew had the highest per unit volume costs, and narrowest optimal spacing. Corridor width had some influence on spacing because the variable operating costs in wide corridors was lower than narrow corridors and had wider optimal corridor spacing. Optimal spacing for narrow and wide corridors at Site II was identical. The only difference in costs between the two systems was in fixed components of the yarding cycle ($\alpha_0$ values) and variable skyline corridor yarding costs ($\beta_1$ values) neither of which affect optimal spacing. Hence,
increasing variable costs or decreasing the fixed costs of moving and development will result in narrower corridor spacing.

Table 16. Optimal Yarding Corridor Spacing and component costs for Site I and Site II.

<table>
<thead>
<tr>
<th>Harvesting Equipment / Corridor Spacing / Crew Size</th>
<th>Swing Yarder Narrow 2-man</th>
<th>Swing Yarder Narrow 4-man</th>
<th>Swing Yarder Wide 2-man</th>
<th>Swing Yarder Wide 3-man</th>
<th>Stationary Yarder Narrow</th>
<th>Stationary Yarder Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Cost ($/hr)</td>
<td>105.28</td>
<td>162.8</td>
<td>105.28</td>
<td>129.47</td>
<td>92.78</td>
<td>92.78</td>
</tr>
<tr>
<td>Component A₀ ($/m³)</td>
<td>9.8080</td>
<td>12.5107</td>
<td>9.2848</td>
<td>10.9759</td>
<td>3.5230</td>
<td>3.3590</td>
</tr>
<tr>
<td>Variable Costs ($/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A₁ ($/m³)</td>
<td>1.4555</td>
<td>0.9060</td>
<td>1.4081</td>
<td>1.3451</td>
<td>0.4965</td>
<td>0.4965</td>
</tr>
<tr>
<td>B₁ ($/m³)</td>
<td>2.5306</td>
<td>3.9132</td>
<td>2.0598</td>
<td>2.5331</td>
<td>1.5319</td>
<td>1.3833</td>
</tr>
<tr>
<td>A₂ ($/m³)</td>
<td>2.1330</td>
<td>2.7302</td>
<td>2.0314</td>
<td>2.4982</td>
<td>0.8455</td>
<td>0.8455</td>
</tr>
<tr>
<td>B₂ ($/m³)</td>
<td>0.1315</td>
<td>0.1570</td>
<td>0.1102</td>
<td>0.1355</td>
<td>0.1176</td>
<td>0.1176</td>
</tr>
<tr>
<td>Corridor Spacing (m)</td>
<td>54.10</td>
<td>49.81</td>
<td>58.79</td>
<td>53.34</td>
<td>46.66</td>
<td>46.66</td>
</tr>
</tbody>
</table>

Results from the total cost and optimal spacing analysis is shown in table 17. Perceived cost savings were not realised by the operator at site II as the corridor spacing was much narrower than the optimal, while at Site I the operator was more cost efficient operating with corridor spacing much closer to the optimal. Optimal spacing was higher than the spacing preferred by the logging contractor at Site I (40 m), however the cost differences between total yarding costs at optimal spacing and conventional spacing was low ranging from 0.26 $/m³ (1.1 percent) to 0.56 $/m³ (1.13 percent). At Site II the logging contractor operated at substantially narrower spacing than the optimal - optimal spacing was nearly double the conventional value of 25 m - and the logging contractor incurs added costs of $1.29 $/m³ (more than 12 percent) for
suboptimal spacing. Potential cost savings could be used as an incentive to convince the logging contractors to increase spacing as a means for decreasing the area clearcut for corridors. For example, the average skyline logging contractor in second growth partial cutting harvests approximately 10,000 m$^3$/year: the cost savings for the contractors would be 5600 $/year to 12,500 $/year (a substantial sum for a small contractor) for Site I and Site II. Reducing the number of corridors would also serve to decrease damage to residual trees given most scarring occurs within 5 m of the yarding corridor.

Table 17. Comparison of actual and optimal skyline corridor spacing (m) and total yarding costs ($/m$^3$).

<table>
<thead>
<tr>
<th>Machine / Corridor width / Crew</th>
<th>Corridor spacing optimal (m)</th>
<th>Corridor spacing actual (m)</th>
<th>Costs at optimal spacing ($/m^3$)</th>
<th>Costs at actual spacing ($/m^3$)</th>
<th>Difference ($/m^3$)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Yarder Narrow 2-man</td>
<td>54.10</td>
<td>40.00</td>
<td>18.69</td>
<td>19.09</td>
<td>0.41</td>
<td>2.13</td>
</tr>
<tr>
<td>Swing Yarder Narrow 4-man</td>
<td>49.81</td>
<td>40.00</td>
<td>23.65</td>
<td>23.91</td>
<td>0.26</td>
<td>1.10</td>
</tr>
<tr>
<td>Swing Yarder Wide 2-man</td>
<td>58.79</td>
<td>40.00</td>
<td>17.31</td>
<td>17.87</td>
<td>0.56</td>
<td>3.13</td>
</tr>
<tr>
<td>Swing Yarder Wide 3-man</td>
<td>53.34</td>
<td>40.00</td>
<td>20.26</td>
<td>20.64</td>
<td>0.38</td>
<td>1.84</td>
</tr>
<tr>
<td>Stationary Yarder Narrow</td>
<td>46.66</td>
<td>25.00</td>
<td>9.20</td>
<td>10.49</td>
<td>1.29</td>
<td>12.34</td>
</tr>
<tr>
<td>Stationary Yarder Wide</td>
<td>46.66</td>
<td>25.00</td>
<td>8.89</td>
<td>10.18</td>
<td>1.29</td>
<td>12.72</td>
</tr>
</tbody>
</table>

A sensitivity analysis for fixed costs and corridor spacing was performed to test the models for accuracy and to determine the impact of corridor spacing on total costs. The results are shown in Table 19 and Figure 12. Comparing the results to those in Table 16 shows that the optimal spacing models did in fact provide the lowest total cost for all strata. The results are similar to McNeel and Young (1994) in that total costs were not overly sensitive to optimal
spacing (notice the flat parabolic curves in figure 10): for example, the resultant difference in total
cost from varying corridor spacing from 20 m to 100 m (500 percent difference) for the swing
yarder 2-person crew in narrow corridors was 2.80 $/m³ (8 percent difference).

Table 18. Sensitivity analysis of corridor spacing (m) and total yarding costs ($/m³).

<table>
<thead>
<tr>
<th>CS (m)</th>
<th>Swing Yarder Narrow 2-man</th>
<th>Swing Yarder Narrow 4-man</th>
<th>Swing Yarder Wide 2-man</th>
<th>Swing Yarder Wide 3-man</th>
<th>Stationary Yarder Narrow</th>
<th>Stationary Yarder Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>22.24</td>
<td>26.91</td>
<td>21.13</td>
<td>23.76</td>
<td>11.47</td>
<td>11.15</td>
</tr>
<tr>
<td>40</td>
<td>19.09</td>
<td>23.91</td>
<td>17.87</td>
<td>20.64</td>
<td>9.34</td>
<td>9.03</td>
</tr>
<tr>
<td>50</td>
<td>18.74</td>
<td>23.64</td>
<td>17.45</td>
<td>20.31</td>
<td>9.17</td>
<td>8.86</td>
</tr>
<tr>
<td>60</td>
<td>18.66</td>
<td>23.65</td>
<td>17.31</td>
<td>20.24</td>
<td>9.19</td>
<td>8.88</td>
</tr>
<tr>
<td>70</td>
<td>18.74</td>
<td>23.82</td>
<td>17.31</td>
<td>20.33</td>
<td>9.32</td>
<td>9.01</td>
</tr>
<tr>
<td>80</td>
<td>18.91</td>
<td>24.08</td>
<td>17.41</td>
<td>20.52</td>
<td>9.53</td>
<td>9.22</td>
</tr>
<tr>
<td>90</td>
<td>19.15</td>
<td>24.41</td>
<td>17.58</td>
<td>20.77</td>
<td>9.78</td>
<td>9.47</td>
</tr>
<tr>
<td>100</td>
<td>19.44</td>
<td>24.78</td>
<td>17.79</td>
<td>21.07</td>
<td>10.06</td>
<td>9.75</td>
</tr>
</tbody>
</table>
A sensitivity analysis was performed to test the impact of fixed costs on corridor spacing. The results are shown in table 18 and figure 13. The analysis showed that a 500 percent increase in the fixed costs of moving and setting up the equipment and development costs resulted in a 130 percent increase in corridor spacing, which corresponds to results shown by McNeel and Young (1994). This is misleading compared to results shown on page 75 where lower variable operating costs (and lower overall total yarding costs) exhibited wider optimal corridor spacing: in fact, increasing moving and set-up time and development costs will afford narrower corridor
spacing, but the total yarding costs will be higher. There are two reasons: first, fixed costs are in the numerator of the corridor spacing equation and variable operating costs are in the denominator, so it stands to reason that increasing the fixed costs will increase corridor spacing; and second increasing moving and development costs while holding variable costs fixed (rarely occurs), will increase corridor spacing in order to reduce the number corridors - and moves and number of corridors to engineer - per harvest area.

Table 19. Sensitivity analysis of fixed costs (cost of moving and development - $/m³) and corridor spacing (m).

<table>
<thead>
<tr>
<th>FIXED COSTS ($)</th>
<th>Swing Yarder Narrow 2-man</th>
<th>Swing Yarder Narrow 4-man</th>
<th>Swing Yarder Wide 2-man</th>
<th>Swing Yarder Wide 3-man</th>
<th>Stationary Yarder Narrow</th>
<th>Stationary Yarder Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>54.10</td>
<td>49.81</td>
<td>58.79</td>
<td>53.34</td>
<td>46.66</td>
<td>46.66</td>
</tr>
<tr>
<td>300</td>
<td>66.72</td>
<td>61.29</td>
<td>72.64</td>
<td>65.76</td>
<td>57.78</td>
<td>57.78</td>
</tr>
<tr>
<td>400</td>
<td>77.30</td>
<td>70.95</td>
<td>84.23</td>
<td>76.18</td>
<td>67.09</td>
<td>67.09</td>
</tr>
<tr>
<td>500</td>
<td>86.59</td>
<td>79.43</td>
<td>94.42</td>
<td>85.34</td>
<td>75.25</td>
<td>75.25</td>
</tr>
<tr>
<td>600</td>
<td>94.99</td>
<td>87.10</td>
<td>103.60</td>
<td>93.61</td>
<td>82.61</td>
<td>82.61</td>
</tr>
<tr>
<td>700</td>
<td>102.69</td>
<td>94.14</td>
<td>112.04</td>
<td>101.20</td>
<td>89.37</td>
<td>89.37</td>
</tr>
<tr>
<td>800</td>
<td>109.86</td>
<td>100.69</td>
<td>119.88</td>
<td>108.26</td>
<td>95.65</td>
<td>95.65</td>
</tr>
<tr>
<td>900</td>
<td>116.59</td>
<td>106.84</td>
<td>127.24</td>
<td>114.89</td>
<td>101.55</td>
<td>101.55</td>
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<tr>
<td>1000</td>
<td>122.95</td>
<td>112.66</td>
<td>134.20</td>
<td>121.16</td>
<td>107.11</td>
<td>107.11</td>
</tr>
</tbody>
</table>

Figure 13. Graph of corridor spacing and fixed costs (moving and development costs).
4.0 Conclusions

Partial cutting has not been practised in coastal British Columbia on a large scale in almost 60 years, largely because of an abundant supply of large raw material, and for economic and topographic reasons. In addition, equipment used in traditional clearcut harvesting has not been suited for partial cutting applications. Partial cutting harvesting systems are becoming popular for three reasons. First, intellectual and physical urban sprawl has caused forest managers and government regulators to adopt forest harvesting practices that maintain some type of continuous forest stand cover is limiting clearcutting operations. Second, mature forest stands denuded by harvesting and natural catastrophes 50 to 100 years ago are suitable for silvicultural treatments involving partial cutting systems, and, third, dwindling levels of old growth forests have caused the forest industry to look for alternative sources of logs, such as harvesting incipient mortality from mature second growth stands. The lack of information and experience in partial cutting operations provided the motivation for this study.

Engineering of partial cutting operations for cable yarding systems is time consuming and requires a higher level of planning than clearcut block layout, because harvesting is restricted to a web of corridors and rows interspersed among residual trees. The true challenge is the iterative process of spacing tailspar trees and landings for skyline corridors to ensure economic harvesting operations. It is essential to have a logging plan that considers all factors including spar tree and landing locations, falling pattern and direction, and locations and loadpath analyses for yarning corridors, and while considering other natural resource values. In cutblock design it is important to consider size, strength, vigour and species of taillspars and tailhold trees, and to have clearly
defined silvicultural objectives for locating skyline corridors and lateral rows in order to minimise the impact of harvesting on stand structure while maximising economic returns.

In steep rugged terrain spatial distribution of landings, tailspar trees, and skyline corridors will be varied and more difficult to locate than in the study areas. As pressure to limit clearcut logging gains momentum, it is essential that the forest industry acquire experience and knowledge about these harvesting systems and their design. Mistakes are certain to occur: learn from them.

The stationary yarder and the swing yarder both had specific advantages and disadvantages in partial cutting, however these differences resulted in only minor variations in productivity between the two machines as shown by the simulations. Most of the variation in productivity observed between the two study sites and the machinery can be attributed to differences in the size of trees harvested and the resulting log sizes. The swing yarder had higher productivity, because of faster line speeds, more manoeuvrability, less time spent moving due to simple guyline rigging, and more power. The stationary yarder is cheaper to operate and the controls are at ground level which permitted the operator easier access to deck piles for unhooking. Differences in cost observed between the two systems were more pronounced owing principally to higher capital and operating costs of the swing yarder.

Results from simulated costs and productivity of the swing and stationary yarders showed that costs and production were comparable when harvesting smaller timber as at Site 1. Swing yarder productivity was noticeably higher and costs lower when harvesting larger timber like at Site II. The stationary yarder showed some increases in productivity with larger timber but not as significant as the swing yarder. The contractor with the swing yarder should focus on forest stands with larger average piece size, whereas piece size is less of an issue for the stationary
yarder. Both contractors would benefit considerably from more advance planning of their operations. In particular, the design and layout of yarding corridors could be improved especially with respect to spacing. Tailspar and landing selection and skyline corridor layout would benefit from loadpath analysis which would help minimise hangups during yarding and damage to residual trees and would lead to higher production rates.

Wide or wedge-shaped yarding corridors promoted higher productivity and lower yarding costs compared to conventional shaped corridors specified in the harvesting guidelines. The swing yarder responded significantly to wider corridors, while response of the stationary yarder was much less marked. Wider corridors provided the swing yarder with more room in the landing to manoeuvre facilitating more efficient decking of logs and unhooking of turns. Wider corridors permitted better sight lines and more room within the corridor for both machine operators to avoid obstacles, position carriages, and break out turns. Wider corridors provided more options for the selection of rub trees to be left along corridors, which helped control the level of damage to the residual stand. Also, wider corridors meant more clearcut area per harvest area which benefited production, but may not meet silvicultural and stand level objectives. However, it is possible to increase logging production through wider skyline corridors by changing operational constraints to match silvicultural objectives which vary by site, instead of the compulsory adoption of universal operational constraints based on generalities which give credence to neither specific site or harvesting equipment characteristics (current situation). Here are two examples. First, at Site I the average residual stand spacing objective was set at 5.7 m; why not allow corridor widths of 5.0 m (allowing for some residual removal along the corridor edge due to excessive damage) instead of the regulatory 3.0 m width, if the result is higher production and
lower costs? The lower costs could result in less damage to the site and residuals because the logging contractor can afford to be more cautious, and public revenue will increase with higher timber sale bids on crown lands. Second, allow a wedge shaped corridor for swing yarders: a regulation rectangular corridor at 3.0 m wide and 150 m long is 450 m$^2$ in clearcut area and equal to a 6.0 m wide at the landing wedge-shaped corridor which is 50 m long.

The production was considerably higher when a skidder and fourth crew member was added to the swing yarder. The landing was kept continually clear of logs which facilitated easy decking and unhooking of logs. However, the costs of the extra equipment and crew was not offset by the increases in productivity.

For cable yarders machinery clearcut harvesting had much higher productivity and was much cheaper than partial cutting. Clearcutting has fewer obstacles, allows larger turns to be built, produces more logs per unit area (based on the same stand), and is much less expensive in terms of move, set-up, planning, and development costs. However, a continuous forest canopy, other resource values which limit clearcutting, or thinning entries into forest stands may be the objectives of the land owner, in which case it will be desirable for the landowner to consider operational factors that will minimise the cost of partial cutting operations. The stumpage appraisal system for coastal BC is based on clearcutting with little and insufficient allowances for the difficulties and added costs of partial cutting. This a major deterrent to partial cutting harvesting systems in coastal BC, and a more equitable cost allowance may encourage further interest from loggers and forest managers.

Potential cost savings exist for both harvesting systems if yarding corridors are spaced at the economically optimal distance. Wider spacing of corridors has the added benefit of reducing
the total area cleared for installation of corridors, and may reduce damage to residual trees by reducing the total area within five meters of the yarding corridors where most of the damage occurs. The combination of wider corridors and wider corridor spacing could be used to maintain the area cleared at the desired level while affording significant cost savings to the contractor. When timber is sold by competitive bid, these cost savings would undoubtedly be reflected in higher bids and increased stumpage revenues for the Province.

What conditions are necessary to maintain a viable partial cutting industry? First what is required is a co-ordinated planning system that manages future forest products and crops by customising silvicultural objectives and treatments with forest harvesting systems which meet the changing stand site conditions prevalent in coastal BC. More field studies are necessary, in order to provide forest managers and loggers with confidence and knowledge in development, harvesting, and the impacts of partial cutting in the coastal setting. Information from field studies should be used to develop an equitable appraisal system which takes into consideration the added costs of partial cutting, and in turn will create more opportunities for partial cutting. Cooperation between sawmills and loggers is necessary to develop markets and conversion plants which utilise smaller diameter timber common in partial cutting. Lastly, and most important is the development of a coastal partial cutting certification program that would require loggers and forest managers to attain a basic level of training in: forest operations and silvicultural systems and treatments, matching silvicultural systems and harvesting systems, engineering and block design for partial cutting harvesting systems, the cause and impact of damage to the residual forest stand, and basic costing and financing of forest harvesting operations. Training of loggers and forest
managers will lead to better forest management, and an understanding of methods of cost saving such as optimal skyline corridor spacing.

Hopefully the forest industry will embark on partial cutting endeavours with the expertise, knowledge and innovation of the last century of logging. British Columbia is a unique region of the world for growing forests, and as the scope of the forest industry changes and the expanding boundaries of urban sprawl impact traditional logging methods, it is the responsibility of forest managers to utilize partial cutting to maintain the sustainability of this truly great resource.

Dag Rutherford, R.P.F.

To live is to battle with trolls
    in the vaults of heart and brain.
To write: that is to sit
    in judgement over one's self.

Henrick Ibsen
5.0 Literature Cited


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