Young Stand Thinning in Western Oregon: Cost Comparison of Harvesting Alternatives and Comparison of Time Study Techniques.

by

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AN ABSTRACT OF THE THESIS OF

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Abstract Approved: ________________________________
Eldon D. Olsen

Harvesting costs were determined for commercial thinning of young stands to achieve vegetation and wildlife objectives. This included replicated comparisons of thinning treatments. Treatments were defined based on residual tree stocking after thinning. Study procedures were developed and evaluated to improve statistical relevance.

Multiple linear regression models were used to compare cycle times of thinning treatments. Indicator variables were found to be effective in evaluating the treatment effects. Extraction costs of harvesting and 95% confidence intervals were determined for skyline yarding, tractor skidding and mechanized systems.

There is not a marked difference in costs between treatments except the heavy thinning treatment of the tractor site. Also the light with openings treatment was more expensive in the mechanized forwarding. Skyline yarding costs are approximately double tractor skidding costs. Skyline costs are more sensitive to yarding distance than tractor skidding. Mechanized harvester costs are higher than manual felling costs.

When extraction distance increases the harvester-forwarder system becomes less expensive than the felling-skidding system.

Harvesting delay analysis for small and large delays shows that mean delay frequency and duration are not significantly different between treatments. Kolmogorov-Smirnov test results show that delay frequency and delay duration distribution of both small and large delays fit the Poisson and exponential curves respectively.

The length of study needed to achieve reasonable delay percentage estimates are roughly equivalent to those needed to achieve delay free cycle time estimates. Simulation of delay demonstrated the need for long study periods to correctly estimate the large delays, which are tracked in shift level studies. A study length of 334 cycles for small delays and 140 days for large delays were predicted with 90% confidence intervals of ±2% and ±3.68% respectively.

Comparison of detailed time study versus shift level study shows that although there is no significant difference in predicted means, the 95% confidence interval in shift level studies is much wider than the detailed. To attain an interval width of ±0.20 cycles per hour a detailed time study would be run for 4 days and a shift level could achieve this level only after 171 days.

Doctor of Philosophy thesis of Mohammad Mozaffar Hossain presented on May 15, 1998

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mohammad Mozaffar Hossain, Author

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YOUNG STAND THINNING IN WESTERN OREGON: COST COMPARISON OF HARVESTING ALTERNATIVES AND COMPARISON OF TIME STUDY TECHNIQUES.

Chapter 1

INTRODUCTION

Currently there is a high interest in manipulating stand structure in Pacific Northwest conifer forests to achieve wildlife objectives. To this end, several new thinning treatments (depending on residual tree stock) and patterns have been proposed for young Douglas fir stands in Central Western Oregon. This thesis will do a cost comparison of these harvesting alternatives. Other scientists are studying stand response, soil impact, stand damage, as well as wild life response. Sixteen units were selected for thinning to represent different possible scenarios. The overall design of the research sites was a compromise which best served all of these research interests.

The costs of commercial thinning is an important factor for deciding the appropriate prescription for a specific situation. The costs may vary among silvicultural thinning intensities, among different locations, and among the logging systems employed.

This thesis will develop the analysis procedure for comparing the extraction costs. In order to detect if dollar per cubic meter cost differences are statistically significant, the variance term must be developed.

In chapter 2, a procedure for calculating the variance will be developed and demonstrated. The variance of the cost will combine the individual variances which are generated by the cycle time, the delays, and the volume per cycle. The procedure will then be demonstrated on the sixteen units.

The source of data are detailed time studies and shift level studies from the Willamette Young Stand Project undertaken jointly by the United States Forest Service (USFS) and Oregon State University (OSU). The sixteen units have three thinning treatments: light, heavy, and light with openings; three sites: Walkthin, Tapthin, and Millthin; and three logging systems: small skyline yarding, tractor skidding, and mechanized (cut-to-length). The hypothesis is that standard error can determine if significant cost differences occur between treatments, sites, and logging systems.

Most previous cost studies have concentrated on a single treatment, at a single site and with one logging system. When comparisons of two treatments are done, separate regression models are usually built for each treatment and then compared under some standard set of conditions such as a given yarding distance. The use of statistical significance is usually limited to picking the variables in the cycle time equation. A confidence interval is sometimes calculated for the cycle time. This thesis will employ the use of indicator variables to detect treatment differences rather than building separate models. This will give greater uniformity in the regression models.

The variances in the costs are the main input for testing statistical significance. The variances of the delays and volumes are as important as the cycle time variance, yet they are rarely formally considered. The variance of the volumes will be obtained from cycle information on number of pieces. The delay variances however are not readily available and have never previously been reported in harvesting research.

Chapter 3 will do a comprehensive analysis of delays and their variances. The first step is to determine whether there is a difference in the amount of delay based on treatments. If there is not, then the delay information can be combined for each site and logging system. Chi-squared contingency tables will be used to test if treatment differences exist. On the other hand, since the equipment and crew change between sites, it is assumed that differences in delays exist and no attempt is made to combine the site delays.

Delay information contains a large amount of variation. The limited length of observation of most field studies falls short of the sample sizes needed to establish good information of the variance of the delays. This thesis will attempt to establish the variance by identifying the underlying statistical distributions. The variance can then be implied from the statistical distributions.

Chapter 3 will do goodness-of-fit tests to identify the delay distributions. The delays will be described by both their frequency of occurrence and their duration. The hypothesis is that these are the Poisson and exponential distributions respectively. The delays are arbitrarily divided into two categories, large delays over 10 minutes and small delays under 10 minutes. The large delay information comes from shift level studies and the small delay data come from detailed time studies.

The frequency and duration distribution variances can be combined to estimate the variance of the percentage of delays that are occurring. Once the delay data has been adequately described, the effect of the study length on the variance can be demonstrated.

Chapter 4 uses simulation to demonstrate how the estimate of the percentage delay improves with longer study periods. Replicated simulations of both large and small delays will show how the percentage of delays slowly converges to the true population value. This will demonstrate the inadequacy of current delay analysis in harvesting research.

Chapter 5 will attempt to integrate the information of the previous chapters in showing the relative confidence intervals that result from detailed time studies and shift level studies. By using regression, the value of shift level data is enhanced and its variance can be established. This is done for cycle time only, since the previous chapter showed the delay variances. These results will allow researchers to plan the level of accuracy that can be obtained from each of these time study methods as well as the impact of different study lengths. The researchers can then determine how much technical manpower should be allocated to detailed time studies versus shift level studies.

Chapter 6 will summarize the thesis that an improved method of cost analysis is necessary and available. This is accomplished with a statistically valid comparison of harvesting methods using a variance which includes delays and volume as well as the traditional variance from only cycle time. The relative value of detailed and shift level studies will be shown with their converging confidence intervals as the study length increases.

The availability of such a large amount of comparable data is seldom available in harvesting research. This allows a more complete estimate of confidence intervals on logging costs. This gives the opportunity to show the variation expected from different logging sites and from different harvesting equipment.

Chapter - 2

REGRESSION MODEL BUILDING AND COMPARISON OF ALTERNATIVES

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INTRODUCTION

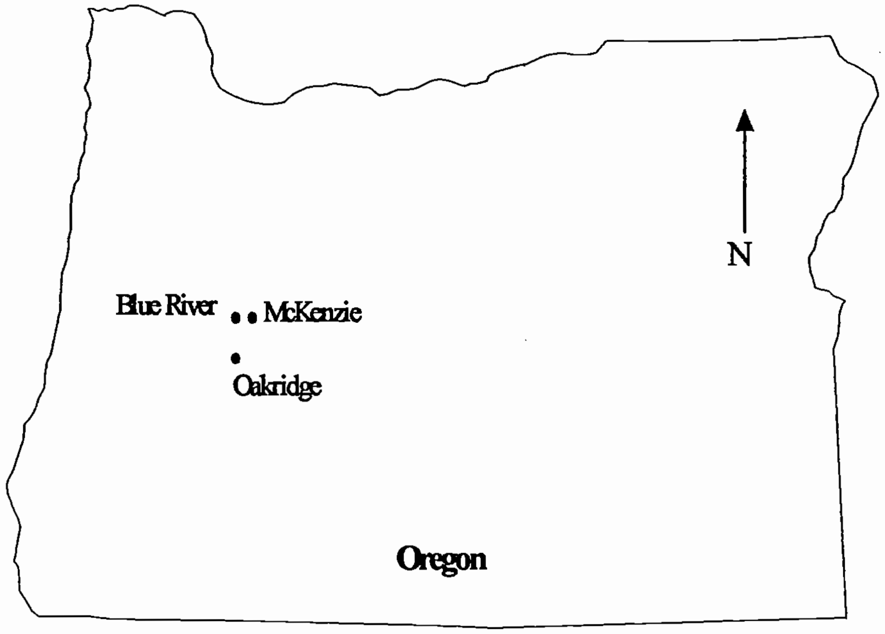
Staffs from the Willamette National Forest and Oregon State University have started a joint study on managing young conifer stands for multiple resources in the Central Western Cascades of Oregon. Young (35 to 55 year old) Douglas-fir stands are the target of intensive management in the next several decades (Kellogg, 1993). Concurrent research is being done on the response of vegetation and wildlife to thinning regimes. This report's focus is on harvesting production rates and costs.

The overall study design consists of four replications of four silvicultural treatments (Kellogg, et al., 1997):

1. "Control" (no thinning), with approximately 618 trees per hectare (250 tpa).
2. "Light thinning", leaving 272-296 residual trees per hectare (110-120 tpa).
3. "Light thinning, with small opening" (0.2 hectare (0.5 acre) opening in 20% of the stand). After logging, the openings were planted with a mixture of Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*).
4. "Heavy thinning", leaving 124-136 residual trees per hectare (50-55 tree per acre), followed by underplanting with a mixture of Douglas-fir, western hemlock, and western redcedar.

The sites include units from five thinning sales (Walkthin, Tapthin, Millthin 1, Millthin 2, and Flatthin), which are located in three USFS ranger districts: Oakridge, McKenzie, and Blue River (Figure 2.1). Millthin was administered as two sales, Millthin 1, and Millthin 2, but for simplicity it is referred to as one sale in this study. Since no harvesting was done in the control units, they were not part of this report. Samples of the harvesting unit layouts are shown in Appendix A.

Figure 2.1 Study locations (not in scale).



Stand density, thinning prescription, and tree removal for different treatment, sites, and logging systems are shown in Tables 2.1, 2.2, and 2.3 (Kellogg, et al., 1997).

Each location has been divided into three treatments (light, heavy, and light with openings). Again each treatment is replicated into two sites depending on slope limitation for tractor versus skyline and mechanized versus skyline. Additional summary information of these thinning sales of the Willamette young stand project is shown in Appendix B.

Table 2.1. Thinning density and harvesting intensity of skyline yarding sites in trees per acre

Site	Walkthin			Tapthin			Millthin 1		
Treatment	Pre-Harvest	Post-Harvest	Thinning removed	Pre-Harvest	Post-Harvest	Thinning removed	Pre-Harvest	Post-Harvest	Thinning removed
Light thin	233	115	118	260	115	145	---	---	---
Heavy thin	169	53	116	180	53	127	195	53	142
Light with opening	212	92	141	230	92	138	---	---	---

Table 2.2. Thinning density and harvesting intensity of tractor skidding sites in trees per acre

Site	Tapthin			Millthin1			Millthin 2		
Treatment	Pre-Harvest	Post-harvest	Thinning removed	Pre-Harvest	Post-Harvest	Thinning removed	Pre-Harvest	Post-Harvest	Thinning removed
Light thin	260	115	145	200	115	85	---	---	---
Heavy thin	180	53	127	195	53	142	---	---	---
Light with opening	---	---	---	---	---	---	196	92	104

Table 2.3. Thinning density and harvesting intensity of mechanized site in trees per acre

Site	Flatthin		
Treatments	Pre-Harvest	Post-Harvest	Thinning removed
Light thin	262	115	147
Heavy thin	334	53	281
Light with opening	214	92	122

Because of the interdisciplinary nature of the Willamette Young Stand Project, a uniform name was given to each of the treatments. These names focused on the post harvest condition of the stand no matter what the site location, the equipment system used, or preharvest stocking level. The light thin had a post harvest density of 115 trees per acre. The heavy thin had 53 trees per acre. The light with openings had 0.5 acre openings in 20% of the unit for a density of 92 trees per acre for the entire unit.

The heavy thin treatments tended to be assigned to units with the lowest initial stocking levels. The designation as a heavy thin treatment does not therefore mean that it always had more trees removed than a light thin. In three of the five sites, the heavy thin actually had the fewer trees removed than the light thin. The assignment of the treatments was beyond the control of this thesis.

The use of these treatments in the comparisons of harvesting costs implies that the post harvest condition is more important than the trees per acre removed. This would be true if interference of the residual trees with the harvesting activities was significant. This was not formally evaluated.

Little is known about commercial thinning under these conditions. Appropriate time and motion studies are needed during the logging operation to evaluate harvesting economics. The analysis for this purpose is confined to a single entry harvesting model with roads in place. The time and motion study data collection was done by researchers from the Department of Forest Engineering, Oregon State University.

The effectiveness of three different logging systems will be compared: small skyline yarding system, tractor skidding system, and a mechanized (cut-to-length) system (Kellogg, 1993). The types and specifications of logging equipment and the method used are shown in Appendix C. This Appendix was prepared from Kellogg, et al., (1997 and 1998).

This chapter will focus only on delay free multiple regression models building on skyline yarding, tractor skidding, mechanized harvesting and forwarding operations. The regression models will be constructed based on delay free detailed time study data. The predicted values from the regression models will be used for cost calculation. The mean costs for each treatment will be determined using actual production, current ownership costs and operating costs of the machine, and labor costs of personnel.

Commercial thinning logging production rates and costs along with their standard error for three levels of residual (light, heavy, and light with openings) will be reported.

No detailed analysis or regression model building will be done for the felling and bucking operations. The felling cost data available from the study of Kellogg et al. (1997) on tractor sites will be used here in the same site for calculating total harvesting costs. Total costs of felling and bucking, and tractor skidding will be determined to make it comparable with the total mechanized harvesting and forwarding costs.

The delay analysis on small (less than 10 minutes) and large (over 10 minutes) delays will be described in chapter 3. Small delay data were collected from detailed time study and large delays from shift level studies.

Literature Review

The following are some of the published articles related to the present study. But no study was found that was similar to the present one.

Data collection

A study on tree-length, wheeled skidding operation in northwestern Ontario was done by Cottell,et al. (1971). Three levels of study were conducted simultaneously on the operation: the shift level, in which the measurement of specified factors were made once per shift; the turn level, in which measurements were made once per turn; and the turn-element level, in which each element of every turn was measured. The analysis of this study showed that significant difference in estimates of average production (cunits/hr) among the three levels of study. However, the number of trees per acre, volume per tree, volume per load, and skidding distance significantly affects cycle time and skidding productivity. The analysis also showed that the "bonus factor", a daily measure of the skidding crew's financial incentive had a significant effect at three study levels. The authors finally concluded the importance of the influences of human factors like skill and motivation to improve traditional cost and production models of ground-based skidding.

The following section discussed the comparison of production and costs on the basis of silvicultural treatments. Small equipment was used for small wood thinning operation to make the operation cost effective.

Skyline yarding

Kellogg et al. (1996) for three alternative silvicultural treatments of residual stand densities examined felling and small yarder uphill skyline yarding production and costs. The heavy thin treatment had the highest production rate and was least costly to harvest. Costs of the other two treatments averaged 6% to 12.3% more. They concluded that these differences are probably small enough to allow choosing the most appropriate silvicultural prescription to meet desired management objectives. Differences in logging techniques between the two study sites also affected production rate and costs. They also found that production rates increased and costs decreased with larger trees harvested, higher average volume per log, and higher net-to-gross log scale.

Logging planning, felling, and cable yarding costs were determined by Kellogg et al. (1996) for five group selection treatments and a clearcut in a 90-year old Douglas-fir stand. They found that the clearcut treatment had the lowest total harvesting costs; costs of group-selection treatments were 7.3% to 31.5% higher than the clearcut. Yarding costs associated with road and landing changes, move in and out, set up and tear down had the biggest influence on total costs for each treatment.

The next sections will show the review of ground based thinning operation using alternative tractors and mechanized equipment

Skidding operation

Vaughan (1988) reported the study of seventeen operators of small tractors during an extraction process. The haul distance was the major variable in the cycle time. Average cycle time was in the range 15 to 25 minutes. The productive machine hours were 6.5 per day. Scheduled hours were 7.5 to 8 with one to two breaks of thirty minutes. Their conclusion was that small crawler tractors have proved to be versatile and reliable machines that provide forest owners with an alternative to cable haulers for thinning steep terrain forests where environmental conditions permit their use.

Mechanized harvesting

A study was done to compare relative advantages and disadvantages of cut-to-length and tree-length harvesting systems clear cutting stems of small-diameter softwood in central Alberta (Anderson, 1994). Koehring 618 feller-bunchers, Timberjack 480 grapple skidders, and Denis 2000 stroke delimbers were used in tree-length operation and Single-grip harvesters, double-grip harvesters, and forwarders all manufactured by Rottne were used in cut-to-length operation. The tree-length system averaged 137m^3/person-day while operating in a stand averaging 0.52m^3/tree and 428 m^3/ha. Machine utilization was 79-87% of scheduled work time. The productivity of feller-bunchers and delimbers increased with an increase in average tree size (m^3/tree). The delimbers were more affected by tree size than the feller-bunchers. Average extraction distance and tree size influenced the productivity of the grapple skidders; average load size per turn increased with increase in tree size. The cut-to-length system averaged

40.6m^3/man-day in a stand averaging 0.22m^3/tree, and 234m^3/ha. The machine utilization time was 69-74% of scheduled work time. Average tree size (m3/tree) and the ratio of unmerchantable-to-merchantable trees in the stand influenced harvester productivity, while the forwarder productivity varied with average extraction distance and harvester created volume of wood on piles (m^3/pile). In the analysis, a lower level of fiber utilization was observed in the tree-length operation compared to cut-to-length operation. This is attributed to a difference in method of payment to operators. They didn't find any evidence that equipment in one method is more capable than that of others. Detailed-timing data on machine productivity for both systems were used for cost analysis. The study compared the operating cost of cut-to-length and tree-length systems but didn't include data on log value delivered to the mills.

The FERIC report (Richardson, et al., 1994) presents a synthesis of information from its studies of cut-to-length systems conducted in eastern Canada. A mechanized cut-to-length system consists of harvesters and forwarders, or of feller-bunchers with processors and forwarders. Productivity for harvesters ranged from 4 - 22m^3 per productive machine hour (pmh), from 12-34m^3/pmh for processors and from 12-31m^3/pmh for forwarders. There were many factors influencing harvester and processor productivity. The most significant factor was the average tree volume. The ratio of the number of unmerchantable trees per ha to the number of merchantable trees per ha, and the number of years of experience of the operator also affected the harvester productivity.

The study reported that cut-to-length systems are more expensive than mechanized full-tree operations when considering only owning and operating costs.

When other costs, like, road costs, infrastructure costs, reforestation costs, slash treatment costs, and moving between cut blocks costs are included, cut-to-length systems may be more economical than full-tree system.

After this review of the comparative study of alternative machines and their performances in different harvesting methods we will now review the techniques of regression model building with indicator variables.

Indicator variables

Some of the variables in harvesting situation are quantitative and measurable. While others are qualitative nature and can usually not be measured directly. Samset (1990) used indicator variables for qualitative variables in time-consumption study working with pine species versus spruce.

Olsen et al. (1998) demonstrated that the individual means or indicator variables can be used for the purpose of comparing silvicultural thinning treatments. Lei (1995) used regression models to compare various treatments using indicator variables. He built a regression model on the effect of growth rate and cambial age on wood properties in red alder and Oregon white oak.

Combined variation

Previous studies on comparing production and costs of alternative methods and equipment often only used the average production. The standard error terms in the components of the logging costs were often neglected. We will introduce in this study the standard error term associated with each component of logging cost calculations. Theory of addition, subtraction, and multiplication developed by Riggs, et al. (1996) is applied in this study. For calculating variance of division the method developed by Mood, et al. (1974) is used.

Description of individual means versus indicator variable approaches

Our purpose is to show how these statistical approaches fit harvesting research studies specifically with relation to distributions. There are two approaches to see whether treatment means are different when using multiple linear regression. These are (1) individual means approach and (2) indicator variable approach. The individual means approach regresses each treatment data set separately. A single set of representative independent variables is chosen to insert into the separate treatment equations. Mean turn time values, thus, for each of the treatments will be obtained. Using the standard error (mean square error) values from the regression, a t-test is performed to see if a significant difference exists between the means.

The indicator variable approach, on the other hand, combines all treatments into a single data set and includes indicator variables to identify the treatments. One of the treatments is picked as the base. The indicator variables then represent the comparison of each treatment against the base. The treatment data are coded to identify the treatments with indicator variables as shown in Table 2.4. The regression of the combined data set then gives a single equation. The statistical significance of the treatment is automatically reported by the P-value for each of the treatment indicator variables. If an indicator variable is significant, its coefficient represents the difference between the treatment mean of that treatment and the treatment mean of the base case.

Table 2.4. Layout of indicator variables representing treatments

	Heavy	Opening	Light_between
Light	0	0	0
Heavy	1	0	0
Opening	0	1	0
Light_between	0	0	1

Combined variation

The variation can be stated as either the variance or as the standard deviation (Olsen, et al., 1998). The standard deviation, which is the square root of the variance, is the most common. When two or more independent random variables are combined then their combined variance can be calculated. For calculating standard error terms for different components of logging cost the following combined variance formulas can be used. Let A and B be two such variables which combine to form a new variable X.

Addition and subtraction (Riggs, et al., 1996)

If $X = A \pm B$

$\mathrm{VAR}(X) = \mathrm{VAR}(A \pm B) = \mathrm{VAR}(A) + \mathrm{VAR}(B)$

$\mathrm{STD.\ DEV.}\ (X) = \sqrt{\{\mathrm{VAR}(A) + \mathrm{VAR}(B)\}}$

Multiplication (Riggs, et al., 1996)

$$\text{If } X = AB$$

$$\mathrm{VAR}(X) = \mathrm{VAR}(AB) = \{\mathrm{MEAN}(A)\}^2\mathrm{VAR}(B) + \{\mathrm{MEAN}(B)\}^2\mathrm{VAR}(A) + \mathrm{VAR}(B)\mathrm{VAR}(A)$$

$$\mathrm{STD.DEV.}(X) = \sqrt{[\{\mathrm{MEAN}(A)\}^2\mathrm{VAR}(B) + \{\mathrm{MEAN}(B)\}^2\mathrm{VAR}(A) + \mathrm{VAR}(B)\mathrm{VAR}(A)\}]}$$

Division (Mood, et al., 1974)

$$\text{If } X = A/B$$

$$\mathrm{VAR}(X) = \mathrm{VAR}(A/B) = \{\mathrm{MEAN}(A)/\mathrm{MEAN}(B)\}^2[\mathrm{VAR}(A)/\{\mathrm{MEAN}(A)\}^2 + \mathrm{VAR}(B)/\{\mathrm{MEAN}(B)\}^2]$$

$$\mathrm{STD.DEV.}(X) = \sqrt{[\{\mathrm{MEAN}(A)/\mathrm{MEAN}(B)\}^2[\mathrm{VAR}(A)/\{\mathrm{MEAN}(A)\}^2 + \mathrm{VAR}(B)/\{\mathrm{MEAN}(B)\}^2]]}$$

A numerical example of these calculations is shown in Appendix D.

Statistical Tools

Quatropro-6 and Exel-97 were used for data management. Statgraphic Plus was used for regression model building and to obtain descriptive statistics. Treatments were compared within the site from regression results by using p-values of the indicator variable representing the treatment. A 95% confidence level was used to test the statistical significance.

Justification of the study

Between the two approaches, individual mean and indicator variable, the latter one is used in this study. The reason for using the indicator variable approach here is the ease of analysis. This approach adjusted the value of the significant variables for all the treatments in the same combined model. Moreover it gives higher R^2 values compared to the individual means approach (Olsen, et al., 1998).

It is very common practice to compare only the means of treatments. In this study the standard error term associated with the mean was also calculated to see the difference of the ranges of two treatments.

The comparison of harvesting costs between the thinning treatments, between sites, and between logging systems are used to demonstrate and achieve the objective of this chapter.

Hypothesis

The standard error term can determine if significant cost differences occur between treatments, sites, and harvesting systems.

Objective of the study

Introducing standard error based on cycle time, delays, and timber volume.

METHODS AND PROCEDURE

Data collection

The detailed time studies were done by handheld computers. The data were then down loaded to personal computer spreadsheets for screening and data management. Two researchers were engaged for collecting all of the data. The study lasted about one week at each of the 15 scenarios. Cycle times were recorded along with associated variables like yarding distance, skidding distance, lateral distance, carriage height, etc. Both small delays (less than 10 minutes) and large delays (over 10 minutes) were recorded for the detailed time study sample days.

Costs data

The source of owning, operating and labor costs associated with the specific equipment and personnel were calculated by Kellogg et al. (1997). A loader is used in combination with tractor(s) in the Tapthin and the Millthin sites. Any unutilized loader time with a particular tractor operation is charged against other operations on the site.

Volume data and unit conversion

Two treatment areas from tractor site were picked and measured volume of logs, tops, and fibers each with sixty trees. These volumes were compared with scaling ticket information. Finally scaling ticket volumes were used in this study because of no significant difference between the two. The cubic feet measurement of volume data were directly converted to metric units.

Logging production and costs

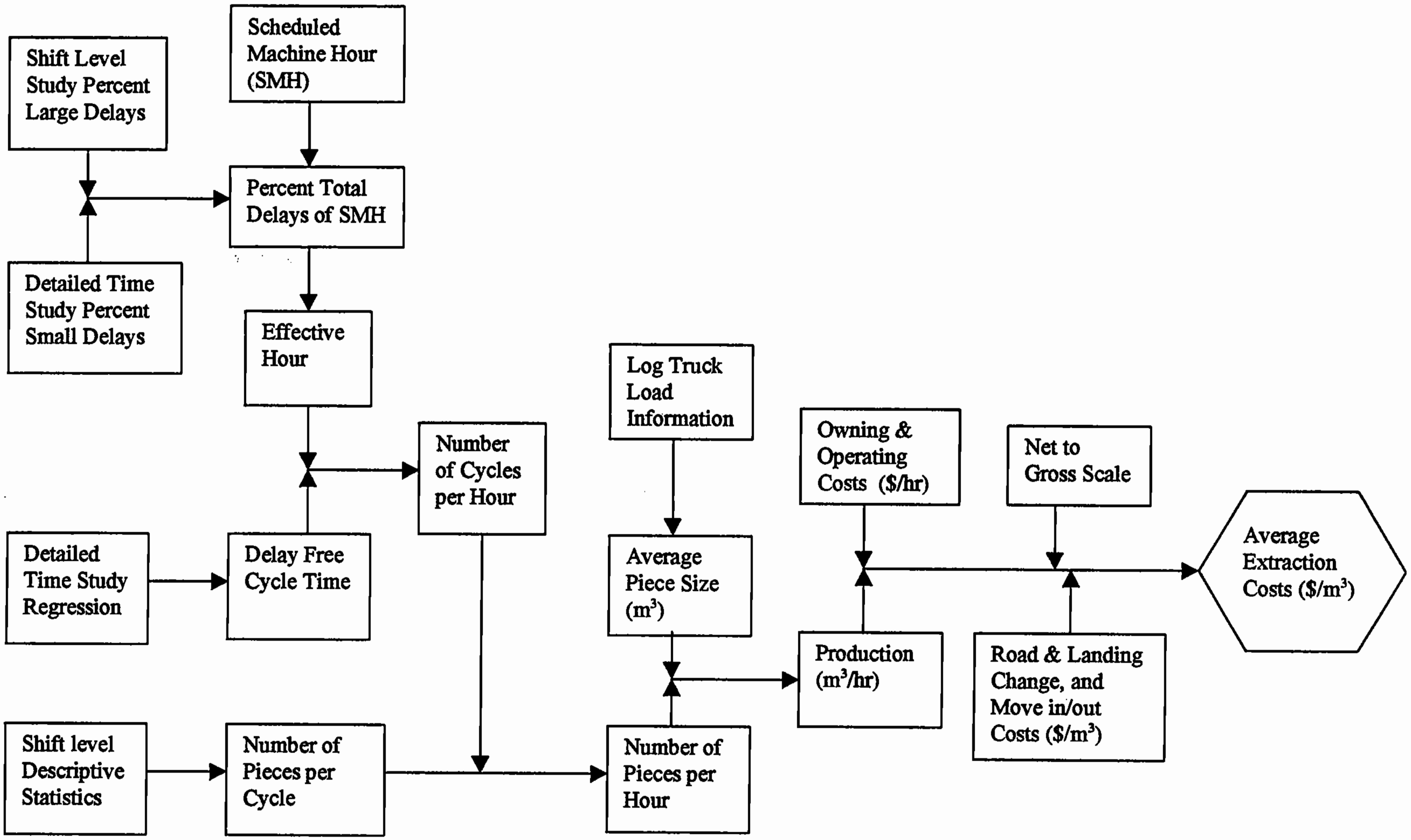
Logging production in m^3 per hour (ccf/hour) and then costs per unit of production ($\$/m^3$ (\$/ccf)) are calculated using the steps of logging production and costs flowchart (Figure 2.2). This flowchart is modified from Matzka (1997). The costs tables were prepared using the flowchart and standard error of flowchart components (shown in Appendix E) which were calculated with the formula for the theory of combined variation. An example of step-by-step skyline yarding costs and its confidence interval calculations is shown in Appendix D.

Regression model building

Multiple linear regression models were developed on skyline yarding, tractor skidding, and mechanized harvesting and forwarding operations. Delay free yarding, skidding, harvesting and forwarding cycle times were regressed on the operational independent variables. Correlation analysis was done to check the correlation between the independent variables. To avoid multiple colinearity the variables were selected by the stepwise forward regression method of Statgraphics Plus. Indicator variable approach is used here to create regression equations. That is, a single regression model was developed in each site by combining all the treatments by using indicator variables representing the treatment. The predicted values of the cycle time were determined by inserting average values for the independent variables into the regression equation.

After satisfactory regression model building, residual analysis was done to see the pattern of residuals and to locate any remaining unwanted outliers. We considered an outlier a data point more than 3 standard deviations from the mean. We are considering individual data points here and assumed a level of 3 standard deviation as a margin. If a data is outside this level we will throw it out.

Figure 2.2. Logging production and costs flow chart



Skyline Yarding

The brief definitions of dependent and independent variables used in skyline yarding regression equations are given below:

YARD	Delay-free yarding cycle time in minutes
YDIST	Slope yarding distance in feet
LDIST	Lateral yarding distance in feet
CARR-HGT	Carriage height in feet
SPAN	1 = lower end of multispan 0 = single span or upper end of multispan
SLOPE	Slope in percent
LOGS	Number of logs per cycle
TOPS	Number of tops per cycle
FIBERS	Number of fibers per cycle (size 4 in. and 1.5 in. at two ends)
PRESET	1 = preset cycle 0 = otherwise
LIGHT	1 = yarding in light thin treatment 0 =otherwise
HEAVY	1 = yarding in heavy thin treatment 0 =otherwise
OPENING	1 = yarding in half acre opening 0 =otherwise
LGT_BTWN	1 = yarding in light thin part between openings 0 =otherwise

Tractor skidding

The brief definitions of dependent and independent variables used in tractor skidding regression equations are given below:

SKID	Delay-free skidding cycle time in minutes
DIST	One way skidding distance in feet
LOGS	Number of logs per cycle
TOPS	Number of tops per cycle
LEAD	Position of the log with respect to winch line in a zone ± 30^0 off a winch line projection 1 = in lead 0 = otherwise
ROAD	Number of logs skidded to clear the skidtrail or road 1 = log skidded from skid trail 0 = otherwise
OFF	Number of half skidder length outside skid trail to pull the log into the skid trail per cycle
LIGHT	1 = skidding in light thin treatment 0 = otherwise
HEAVY	1 = skidding in heavy thin treatment 0 = otherwise
OPENING	1 = skidding in half acre opening 0 = otherwise
LGT_BTWN	1 = skidding in light thin part between openings 0 = otherwise

Harvesting

The brief definitions of dependent and independent variables used in harvesting regression equations are given below:

HARV	Delay-free harvesting cycle time in minutes
LOGS	Number of logs per cycle (here 1 tree = 1 cycle)
HANGUP	1 = hang-up occurs in a cycle 0 = otherwise
DBH	Diameter at breast height of the tree in inch
DBH^2	Diameter at breast height squared
LIGHT	1 = harvesting in light thin treatment 0 = otherwise
HEAVY	1 = harvesting in heavy thin treatment 0 = otherwise
OPENING	1 = harvesting in half acre opening 0 = otherwise
LGT_BTWN	1 = harvesting in light thin part between openings 0 = otherwise

Forwarding

The brief definitions of dependent and independent variables used in forwarding regression equations are given below:

FORWARD	Delay-free forwarding cycle time in minutes
OUTDIST	Distance from landing to the point where first log is loaded (feet)

LOADDIST	Distance traveled while loading (feet)
INDIST	Distance traveled to landing once fully loaded (feet)
LARGESAW	Number of large saw logs per cycle (here 1 cycle = 1 load)
SAWLOGS	Number of saw logs per cycle
FIBERS	Number of pulp logs per cycle
LIGHT	1 = harvesting in light thin treatment 0 = otherwise
HEAVY	1 = harvesting in heavy thin treatment 0 = otherwise
OPENING	1 = harvesting in half acre opening 0 = otherwise
LGT_BTWN	1 = harvesting in light thin part between openings 0 = otherwise
LGT_OPENING	1 = harvesting in light with opening treatment 0 = otherwise

Validation of regression model

A random sample of 30 (approximately 12% of total data) observations of the detailed time study data was reserved for validating the models. The remaining data are used for regression model building. A paired t-test (0.05 probability level) was done on the reserved data to compare predicted versus actual cycle time on a cycle-by-cycle basis. This is one of the four techniques of regression model validation demonstrated by Howard (1992).

Total extraction costs comparison

Total extraction costs for each treatment area for each of the logging sites was calculated using a cost flowchart. The components of the cost flowchart, the standard error term for each component, and finally the average extraction costs in $/m3 and $/ccf and its 95% confidence interval for each treatment were determined (Appendix E). In calculating confidence intervals of total harvesting costs, the standard error term of the production in each treatment was used. The objectives of this calculation are mainly to compare treatments in each site, similar treatments between/among sites (Walkthin, Tapthin, and Millthin) and between logging systems (skyline, tractor, and mechanized). The t-test is used to compare costs between alternatives. Then graphs of the confidence intervals of mean costs were determined for visual comparison. The reason for calculating standard errors and hence confidence intervals is to see distinctly whether there is any statistically significant difference between the treatment means. This is indicated by the observation of any overlapping between the confidence bands.

Treatment comparison

The results of the regression models are sufficient to compare treatments in each site. As the indicator variable approach for regression model building is used, the coefficient of the significant indicator variable for treatment will indicate the amount of difference of the treatment from the base treatment. Here the limitation is that all treatments can be compared only with the base treatment. In this analysis light treatment is set up as base. In this stage the comparison is on a cycle time basis. Later comparisons of treatments were done after calculating total extraction costs using the costs flowchart. The 95% confidence interval of mean costs was also calculated for comparison. The predicted value of the mean cycle time, used in the cost flowchart, was calculated by using average variable values in the regression equation.

Thinning sites comparison

The treatment cost calculated by the cost flowchart in each site is the basis for comparing across sites. The sites are compared between the same treatment type from different sites. For example, light treatment of skyline yarding system of Walkthin site is compared with that of Tapthin site. Mean extraction cost along with its 95% confidence interval was calculated for comparison. The comparison of sites was also done over a range of extraction distances.

Logging systems comparison

Extraction costs comparison among three systems

Here the extraction costs are compared for the same treatment type among three systems. For example, heavy thin extraction costs between Tapthin skyline yarding, Tapthin tractor skidding and Flatthin forwarder operations were done. For this purpose extraction distance is varied within a range applicable to all systems. Costs using the cost flowchart were calculated for each system for each of the distance. Confidence intervals at the 95% level were also calculated at different distance for comparison of the mean costs.

Felling costs comparison in ground based

The felling costs of tractor site and harvesting costs of mechanized site are compared between the same treatment type of both sites. Diameter at breast height (DBH) varied from 15 cm to 35 cm. Mean costs at both sites for each diameter type along with 95% confidence intervals were calculated for comparison. The example of this cost comparison is between the light thin tractor site manual felling and the light thin harvester operation.

Total costs comparison in ground based

The total harvesting costs of felling and tractor skidding and similarly total costs of harvester and forwarder operations were calculated. The costs along with their 95% confidence intervals are compared between the tractor site and mechanized site for each treatment type.

Comparison limitations and variability

The initial stocking levels were not uniform among treatments or between sites. So although the final stocking levels after harvesting are identical for the same treatment (even between sites and logging systems), the removal rate, measured in trees per hectare, varied a great deal. This introduced uncontrolled and unwanted variation into the comparisons. For instance the heavy thinning did not always result in the highest number of trees removed as would be expected.

Logging crews and equipment were only held constant at each site. Therefore between sites comparisons had many sources of variation.

Two other serious variations occurred due to a mixture of seasons and tree diameter differences among sites. Crew and season were not possible to include as variables because the data were not collected that way.

ANALYSIS, RESULTS AND DISCUSSION

The multiple linear regression equation of each site for each of the logging systems is shown below. The significant variables with their p-values, average variable values, and ranges of variables are shown here.

Skyline Yarding

Walkthin Site

The regression model developed from the detailed time study to predict delay-free mean yarding cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean YARD (min) =	2.6273	0.0000	Constant (min/cycle)	

+ 0.0026 (YDIST)	0.0000	570.28 (feet)	40-1200
+ 0.0122 (LDIST)	0.0000	20.52 (feet)	0-90
+ 0.0026 (CRR_HGT)	0.0455	51.19 (feet)	5-162
+ 0.1360 (SPAN)	0.0406	0,1 (Indicator variable)[1]	0-1
+ 0.2391 (LOGS)	0.0000	1.68 (number/cycle)	0-6
+ 0.1959 (TOPS)	0.0000	1.84 (number/cycle)	0-8
+ 0.1179 (FIBERS)	0.0000	1.21 (number/cycle)	0-8
- 0.4684 (PRESET)	0.0000	0,1 (Indicator variable)[2]	0-1
- 0.7289 (OPENING)	0.0000	0,1 (Indicator variable)[3]	0-1
- 0.4699 (LGT_BTWN)	0.0000	0,1 (Indicator variable)[4]	0-1
- 0.8712 (HEAVY)	0.0000	0,1 (Indicator variable)	0-1

($R^2_{adjusted}$ = 52.7%; Standard Error of $Y_{estimate}$ = 0.741 min/cycle; Sample size = 937cycle)

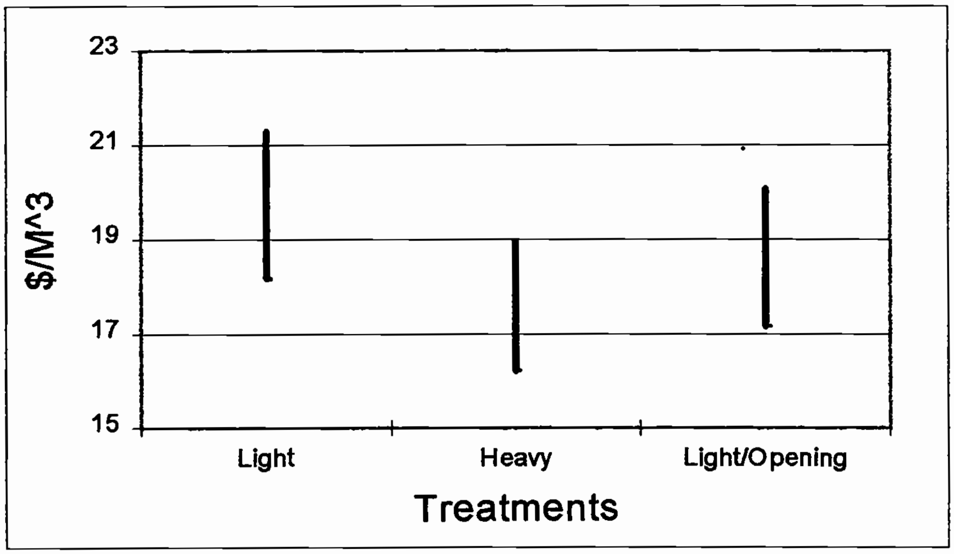
[1] 20% of cycle was multispan.
[2] 18% of cycle was preset.
[3] 20% of area was opening in the treatment.
[4] 80% of area was light thin in between openings.

The variables CHOKERS and SLOPE are not significant in the model. The most influential variable in this equation is the YDIST. The negative sign of indicator variable PRESET means that presetting decreased the mean cycle time by 0.4684 min. That is, the cycle time is shorter by approximately half a minute when logs are preset ahead of time.

The treatments are represented here by indicator variables. The treatment LIGHT is the base in the setup of the model. That is, the light treatment is compared directly versus heavy and versus light with opening treatments. For example, in this model, the heavy treatment mean cycle time is 0.8712 minute shorter than that of light treatment.

Openings and light between openings occupy 20% and 80% respectively of the treatment light with openings. In this case the mean cycle time of light with openings treatment is 0.5217 minutes shorter than that of light treatment. The mean delay free cycle time for light, heavy, and light with openings thinning are 5.17, 4.29, and 4.84 minutes respectively (Appendix E, Table E.1a and E.1b). Therefore heavy thinning cycle is the fastest and light is the slowest in this condition. The resulting costs are shown in Figure 2.3.

Figure 2.3. Comparison of skyline yarding costs between treatments of Walkthin site with 95% confidence interval



Tapthin Site

The regression model developed from the detailed time study to predict delay-free mean yarding cycle time is

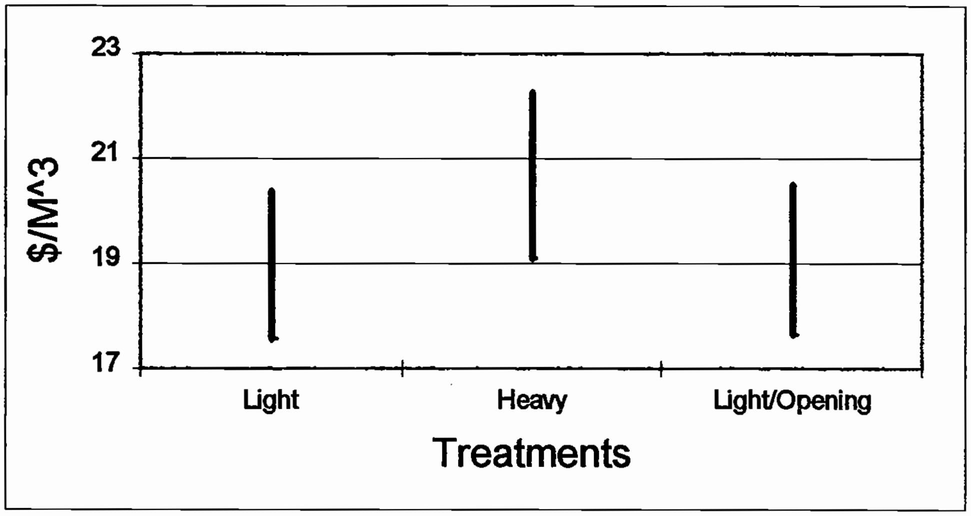
	Coefficient (variable)	P-value	Average value	Range
Mean YARD (min) =	1.231	0.0000	Constant (min/cycle)	
	+ 0.0029 (YDIST)	0.0000	609.83 (feet)	5-1120
	+ 0.0104 (LDIST)	0.0000	20.38 (feet)	0-85
	+ 0.0172 (CRR_HGT)	0.0000	42.03 (feet)	15-70
	+ 0.0119 (SLOPE)	0.0003	16.46 (%)	10-40
	+ 0.1412 (LOGS)	0.0000	2.59 (number/cycle)	0-6
	+ 0.1113 (TOPS)	0.0000	1.30 (number/cycle)	0-4
	+ 0.0783 (FIBERS)	0.0008	0.55 (number/cycle)	0-8
	- 0.6677 (PRESET)	0.0000	0,1 (Indicator variable)[1]	0-1
	- 0.4154 (OPENING)	0.0000	0,1 (Indicator variable)[2]	0-1
	- 0.1857 (LGT_BTWN)	0.0000	0,1 (Indicator variable)[3]	0-1

($R^2_{adjusted}$ = 58.9%; Standard Error of $Y_{estimate}$ = 0.473 min/cycle; Sample size = 671 cycle)

[1] 18% of cycles was preset.
[2] 20% of area was opening in the treatment.
[3] 80% of area was light thin in between openings.

The variables in Walkthin and Tapthin sites are not the same. Slope is an influencing variable in Tapthin yarding where as it was not in the Walkthin site. The cycle time increases significantly with the increase of slope. In the Tapthin site the heavy treatment is not significant at the 95 % level. That means, the average cycle time of the light thin treatment is not significantly different from heavy thin. Differences in the volume per cycle result in costs are shown in Figure 2.4.

Figure 2.4. Comparison of skyline yarding costs between treatments of Tapthin site with 95% confidence interval



Millthin Site

The regression model developed from the detailed time study to predict delay-free mean yarding cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean YARD (min) =	2.394	0.0000	Constant (min/cycle)	
	+ 0.0007 (YDIST)	0.0224	375.46 (feet)	50-910
	+ 0.0209 (LDIST)	0.0000	24.65 (feet)	0-95
	+ 0.0306 (CRR_HGT)	0.0003	32.05 (feet)	5-45
	- 0.0470 (SLOPE)	0.0055	18.01 (%)	0-20

+ 0.3558 (LOGS)	0.0000	3.13 (number/cycle)	1-8
+ 0.5469 (TOPS)	0.0004	0.14 (number/cycle)	0-2
+ 0.4733 (FIBERS)	0.0000	0.35 (number/cycle)	0-3
- 0.7303 (PRESET)	0.0000	0,1 (Indicator variable)[1]	0-1

($R^2_{adjusted}$ = 37.2%; Standard Error of $Y_{estimate}$ = 0.813 min/cycle; Sample size =229 cycle)

[1] 52% of cycle was preset.

The variable SPAN is not significant in the model. The slope variable acts differently in Millthin site. The cycle time decreases with the increase of slope. The Millthin site has only the heavy thin treatment.

Tractor Skidding

Tapthin Site

The regression model developed from the detailed time study to predict delay-free mean skidding cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean SKID (min) =	5.548	0.0000	Constant (min/cycle)	
	+ 0.0037 (DIST)	0.0000	692.6 (feet)	90-1730
	+ 0.3694 (LOGS)	0.0059	4.92 (number /cycle)	2-8
	+ 1.0350 (TOPS)	0.0000	0.15 (number /cycle)	0-4
	- 0.8976 (ROAD)	0.0039	0,1 (indicator variables)[1]	0-1
	+ 2.0129 (HEAVY)	0.0000	0,1 (indicator variables)	0-1

($R^2_{adjusted}$ = 74.42 %; Standard Error of $Y_{estimate}$ = 1.32 min/cycle; Sample size =130 cycle)

[1] Average 19% of logs skidded were to clear the skid trail or road

The variable ROAD causes the cycle time to be 0.9 minute shorter. The reason is that about 19% of the logs skidded were to clear the skid trail or road and no extraction distance is involved for that amount of log pick up for the cycle. The cycle time of heavy thin treatment is 2 minutes longer than that of light thin.

Millthin 1 Site

The regression model developed from the detailed time study to predict delay-free mean skidding cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean SKID (min) =	3.140	0.0000	Constant (min/cycle)	
	+ 0.0041 (DIST)	0.0000	534 (feet)	50-1140
	+ 0.5514 (LOGS)	0.0000	3.95 (number/cycle)	1-8
	- 0.2506 (LEAD)	0.0122	0,1 (indicator variable)[1]	0-1
	+ 0.9318 (ROAD)	0.0012	0,1 (indicator variable)[2]	0-1
	+ 1.1443 (HEAVY)	0.0134	0,1 (indicator variable)	0-1

($R^2_{adjusted}$ = 35.77%; Standard Error of $Y_{estimate}$ = 1.25 min/cycle; Sample size =177 cycle)

[1] Average 3.32 logs/cycle in lead

[2] Average 32 % of logs skidded were to clear the skid trail or road

The variable LEAD decreases the cycle time by 0.25 minute. This is because of the location of the log in the lead (the position of the log with respect to line in a zone of ±30° off a projection of the winch line) where it takes less time to drag than when a log is outside the lead. For instance in this case an average 3.32 logs /cycle were located in the lead out of a total of 3.95 logs/cycle. The ROAD variable causes about 0.93 minute longer cycle time. This is contrary to the previous result obtained in Tapthin site. The forward and backward stepwise methods gave the same result in this case. We left this variable in the model for the sake of consistency. It does not affect much in cycle time. The increase in cycle time in heavy thin treatment is 1.14 minutes more than that of the light thin treatment. The resulting costs are shown in Figures 2.5 and 2.6.

Figure 2.5. Comparison of tractor skidding costs between treatments of Tapthin site with 95% confidence interval

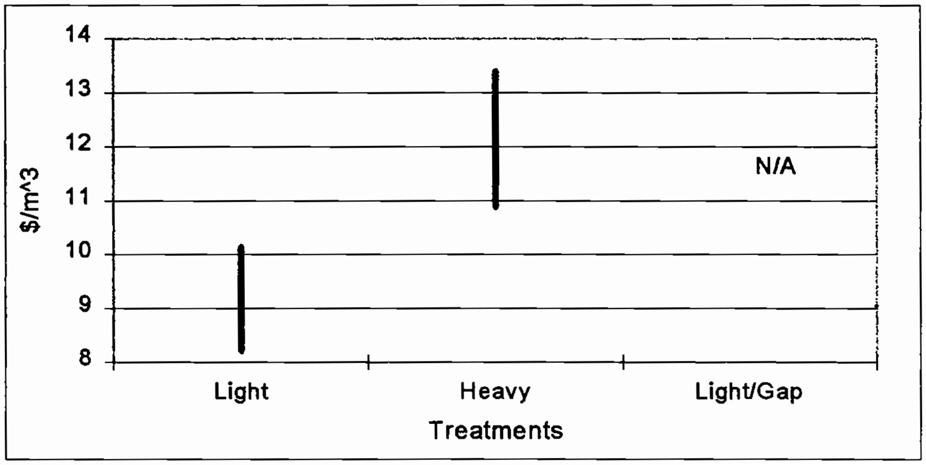
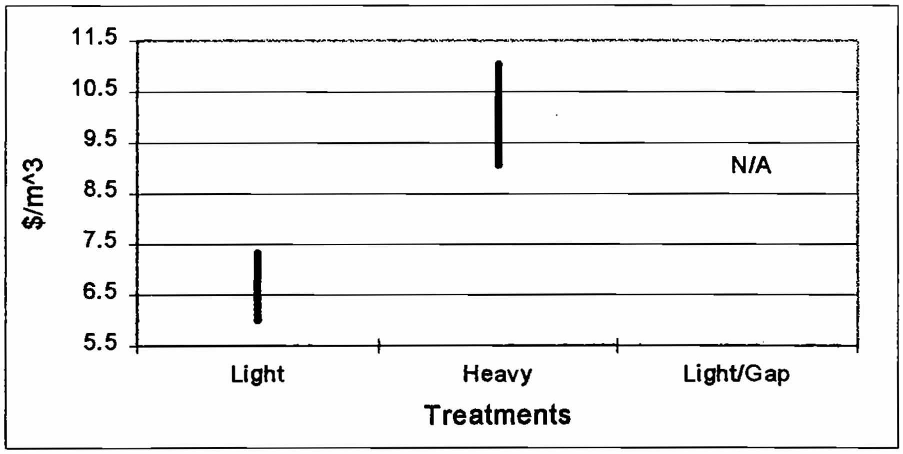


Figure 2.6. Comparison of tractor skidding costs between treatments of Millthin 1 site with 95% confidence interval



Millthin 2 Site

The regression model developed from the detailed time study to predict delay-free mean skidding cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean	SKID (min) = 4.182	0.0000	Constant (min/cycle)	
	+ 0.0068 (DIST)	0.0000	481.9 (feet)	125-870
	+ 0.1673 (OFF)	0.0000	2.83 (number/cycle)	0-20

($R^2_{adjusted}$ = 57.7 %; Standard Error of $Y_{estimate}$ = 1.34 min/cycle; Sample size =66 cycles)

Here the average number of OFF is 2.83 per cycle. The variable OFF causes a 0.17 minute per log per cycle increase. OFF is in relation to the location of the tractor inside or off the road for a turn during winching operation. So it takes more time for a complete cycle for the tractor taking position off the road and then moving on to the skid trail for its subsequent loaded travel.

Harvesting in Flatthin

The regression model developed from the detailed time study to predict delay-free mean harvesting cycle time is

	Coefficient (variable)	P-value	Average value	Range
Mean HARV (min) =	1.197	0.0000	Constant (min/cycle)	
	+ 0.1977 (LOGS)	0.0000	3.28 (number/cycle)	1-8
	+ 0.4343 (HANGUP)	0.0000	0,1 (indicator variable)[1]	0-1
	- 0.2059 (DBH)	0.0000	11.66 (inch)	5-21.8
	+ 0.0106 (DBH^2)	0.0000	151.05 (inch^2)	25-475
	+ 0.1567 (OPENING)	0.0001	0,1 (indicator variable)	0-1

($R^2_{adjusted}$ = 51.51 %; Standard Error of $Y_{estimate}$ = 0.421 min/cycle; Sample size =765 cycles)

[1] 4.7% cycles were hang-ups

Hanging up of the tree during harvester operation increases the cycle time. For this reason the variable HANGUP shows the cycle time increase of 0.43 minute. The quadratic variable DBH^2 increases the cycle time at the rate of 0.01 minute for each unit value of the variable. This is the only curvilinear variable of the regression equation. In the 20% of the cycles within opening (the light with opening treatment) the harvester cycle takes 0.16 minute longer than that of light thin treatment.

Forwarding in Flatthin

The regression model developed from the detailed time study to predict delay-free mean forwarding cycle time is

Coefficient (variable)	P-value	Avg. value	Range
Mean FORWARD (min) = 14.636	0.0000	Constant (min/cycle)	
+ 0.0051 (OUTDIST)	0.0034	856.93 (feet)	90-2170
+ 0.0053 (LOADDIST)	0.0001	291.61 (feet)	30-2540
+ 0.0070 (INDIST)	0.0001	692.21 (feet)	0-2100
+ 0.2533 (LARGE_SAW)	0.0000	5.255 (number/cycle)	0-44
+ 0.0698 (SAWLOGS)	0.0012	51.42 (number/cycle)	0-108
+ 0.0988 (PULP)[1]	0.0000	9.39 (number/cycle)	0-186
+ 11.5297 (LGHT_OPENING)	0.0000	0,1 (indicator variables)	0-1

($R^2_{adjusted}$ = 74.25 %; Standard Error of $Y_{estimate}$ = 4.39 min/cycle; Sample size = 67 cycles)

[1] PULP is same as variable FIBERS in skyline yarding and tractor skidding.

The variable SAWLOG is the most influential variable in the forwarder cycle time. The cycle time of light with opening thin treatment is 11 minutes longer than that of light thin treatment. The costs are shown in Figure 2.7.

Tables 2.5 and 2.6 summarize all of the costs. Table 2.7 is the summary table if statistical difference at 95% confidence level comparing costs between treatments, sites, and logging systems. Calculations for the Table 2.7 are shown in Appendix E Tables.

Figure 2.7. Comparison of Flatthin harvesting and forwarding costs between treatments with 95% confidence interval

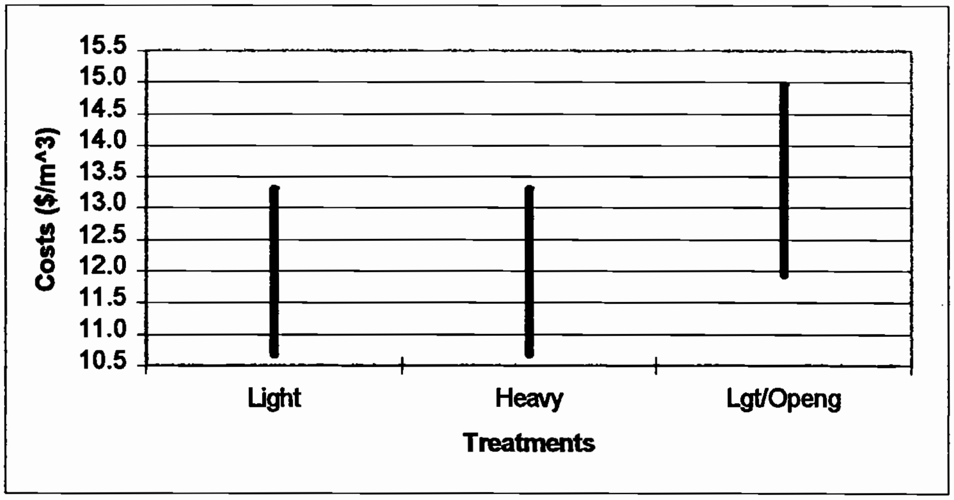


Table 2.5. Mean extraction costs of all sites with confidence interval in Metric unit

Site	Treatments		
	Light ($/m^3)	Heavy ($/m^3)	Light with Opening ($/m^3)
Walkthin yarding	19.98 ±1.63	17.24 ±1.38	18.47 ±1.50
Tapthin yarding	19.05 ±1.46	20.00 ±1.56	20.02 ±1.58
Millthin yarding	N/A	25.96 ±2.51	N/A
Tapthin skidding	9.08 ±0.98	12.00 ±1.29	N/A
Millthin 1 skidding	6.59 ±0.67	9.95 ±1.99	N/A
Millthin 2 skidding	N/A	N/A	7.17 ±0.83
Flatthin forwarding	6.70 ±0.97	6.70 ±0.97	9.12 ±1.32

Table 2.6. Mean extraction costs of all sites with confidence interval in English unit

Site	Treatments		
	Light ($/ccf)	Heavy ($/ccf)	Light with Opening ($/ccf)
Walkthin yarding	56.63 ±4.62	48.85 ±3.92	52.35 ±4.24
Tapthin yarding	53.98 ±4.14	56.66 ±4.42	56.73 ±4.48
Millthin yarding	N/A	73.57 ±7.11	N/A
Tapthin skidding	25.74 ±2.78	34.02 ±3.66	N/A
Millthin 1 skidding	18.69 ±1.90	28.19 ±5.64	N/A
Millthin 2 skidding	N/A	N/A	20.33 ±2.35
Flatthin forwarding	18.99 ±2.75	18.99 ±2.75	25.85 ±3.75

Table 2.7. Summary table of statistical difference at 95% level.
(Same letters in a row show no difference at 95% level).

a. Costs comparison of treatments within site

	Light	Heavy	Light with Opening
Walkthin yarding	A	B	B
Tapthin yarding	A	A	A
Millthin 1 yarding	A	A	N/A
Tapthin skidding	A	B	N/A
Millthin 1 skidding	A	B	N/A
Millthin 2 skidding	N/A	N/A	N/A
Flatthin Forwarding	A	A	B

b. Costs comparison of yarding sites for same treatment type

	Walkthin Yarding	Tapthin Yarding	Millthin Yarding
Light	A	A	N/A
Heavy	A	B	C
Light w/ opening	A	A	N/A

c. Costs comparison of skidding sites for same treatment type

	Tapthin Skidding	Millthin 1 Skidding	Millthin 2 Skidding
Light	A	B	N/A
Heavy	A	B	N/A

Treatment comparison

The regression model reported in each site for each of the logging systems is obtained using the stepwise forward regression method. We did not force any variable into the models to make them uniform. As a result different site models may have different variables. During comparison we chose the same treatment type from different sites. For determining predicted turn times we input common values of the variables. The summary of the confidence intervals for the costs are shown in Table 2.5 and Table 2.6.

Walkthin skyline yarding

The increase or decrease of mean cycle time and hence a decrease or increase of hourly production directly affects the cost of extraction. Here light thin cost is the highest among the three treatment costs and it is significantly different from heavy thin treatment (p-value = 0.0222) (Appendix Table F.1). There is no significant difference between light thin and light with opening thin or between heavy thin and light with opening thin treatments (Appendix Table F.1).

Tapthin skyline yarding

The variable HEAVY is not significant in the regression equation. That means there is no evidence that heavy thin treatment cycle time is significantly different from light thin treatment. There may be statistically different volumes/cycle between treatments. Although there is a shorter cycle time in light with opening treatment than light, due to lower production per cycle the extraction costs are higher than that in light treatment.

Millthin skyline yarding

Heavy thin treatment is the only variable in this model (Appendix Tables E.3a and E.3b).

Tapthin tractor skidding

Heavy thin costs are significantly different from that of light thin cost (p-value = 0.0002). Here heavy thin costs is higher than the light because the heavy thin mean cycle time is 2 minute longer than that of light.

Millthin 1 tractor skidding

Heavy thin costs is significantly higher than that of light thin cost (p-value = 0.0000). The reason for this difference is that heavy treatment mean cycle time is 1.14 minutes longer than that of light.

Millthin 2 tractor skidding

Millthin 2 is a one variable (Light with opening) model.

Flatthin harvesting and forwarding costs

There is no significant evidence that the total cost of Flatthin harvesting and forwarding between light and heavy treatments is different. But the heavy thin costs are significantly different from light with opening thin costs (p-value = 0.0218). Light with opening thin mean forwarding cycle time is 11.53 minutes longer than that of light thin, for that reason production per hour is lower and hence the cost per cubic meter is significantly higher than that of light (p-value = 0.0218).

Sites comparison

When comparing sites, the road and landing changes were included in order to give a complete picture of costs. We do not have road and landing change variation data available. Moreover road and landing change may have very small sample size per treatment. Volume per cycle differences were also incorporated into the calculation.

These comparisons show the range of costs that could be expected when different crews and unique (but not measured) site differences occur.

Light thin skyline yarding costs between sites

Light thin costs between the Walkthin and Tapthin sites is not significantly different (p-value = 0.2399)(Figure 2.8 and Appendix Table F.2). These costs at distance100 m and 300 m are also not significantly different (Figure 2.9) from each other (p-values are 0.1995 and 0.4459 respectively)(Appendix Table F.9). From Figure 2.9 it is observed that extraction costs increases linearly with the increase of distance, but the rate of increase is different for different treatment.

Figure 2.8. Comparison of light thin skyline yarding costs between sites with 95% confidence interval

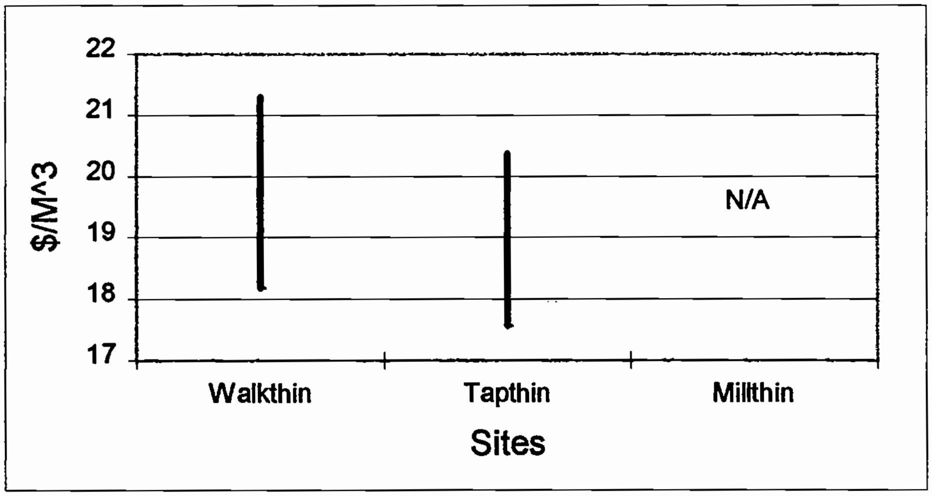
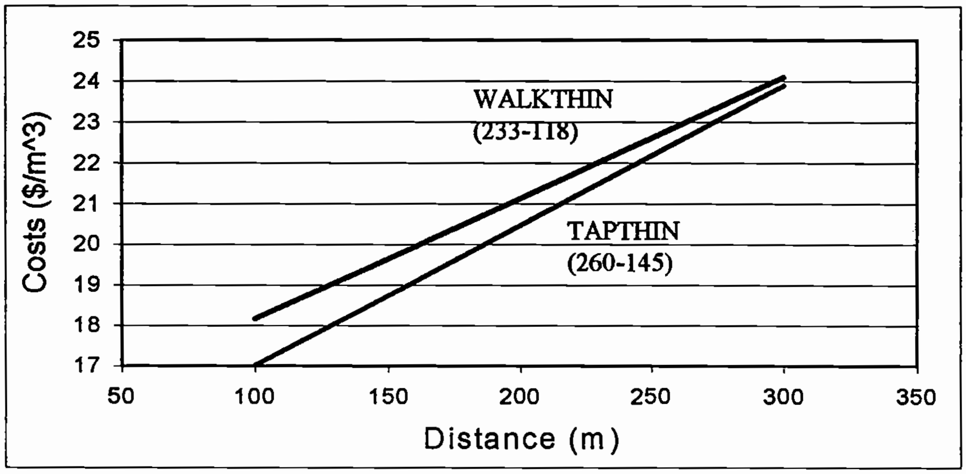


Figure 2.9. Comparison of light thin skyline yarding costs between sites at different distances



(233-118) demonstrates: 233 pre-harvest and 118 harvest removal in trees/acre (tpa).

Heavy thin skyline yarding costs between sites

Heavy thin costs of the Walkthin and Tapthin sites are significantly different from each other (p-value = 0.0022) and heavy thin costs of Tapthin and Millthin sites are significantly different from each other (p-value = 0.0001)(Appendix Table F.3)(Figure 2.10). Although the delay free cycle times for both heavy thin treatments of the Walkthin and Tapthin sites are almost same, the 4.2 min/hr more delay and $53.35 more operating costs per hour (Appendix Table E.1a and E.2a) in Tapthin causes higher costs in Tapthin compared to Walkthin. In the same way, about 1.3 minutes longer cycle time and further 5.3 min/hr more delay in Millthin compared to Tapthin caused higher costs in Millthin (Appendix Table E.2a and E.3a)(Figure 2.10 and 2.11). The residual after removal was 53 and the removals for the three sites were 116, 127, and 142 respectively.

Figure 2.10. Comparison of heavy thin skyline yarding costs between sites with 95% confidence interval

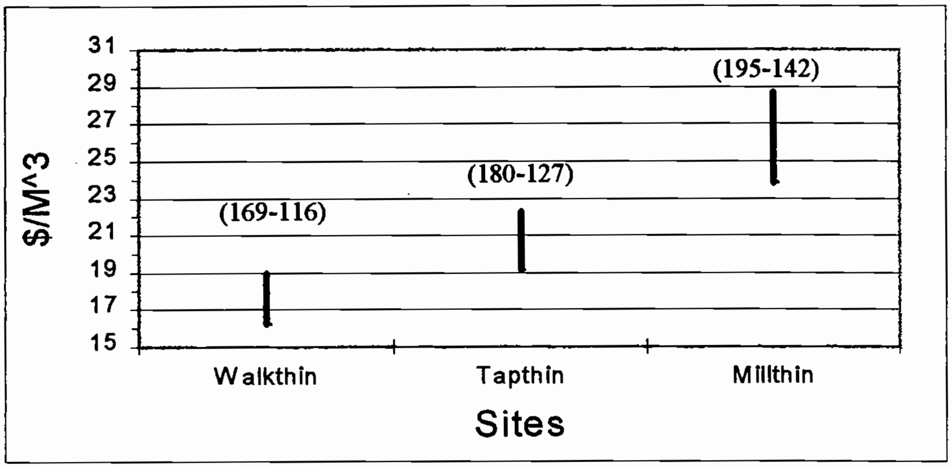
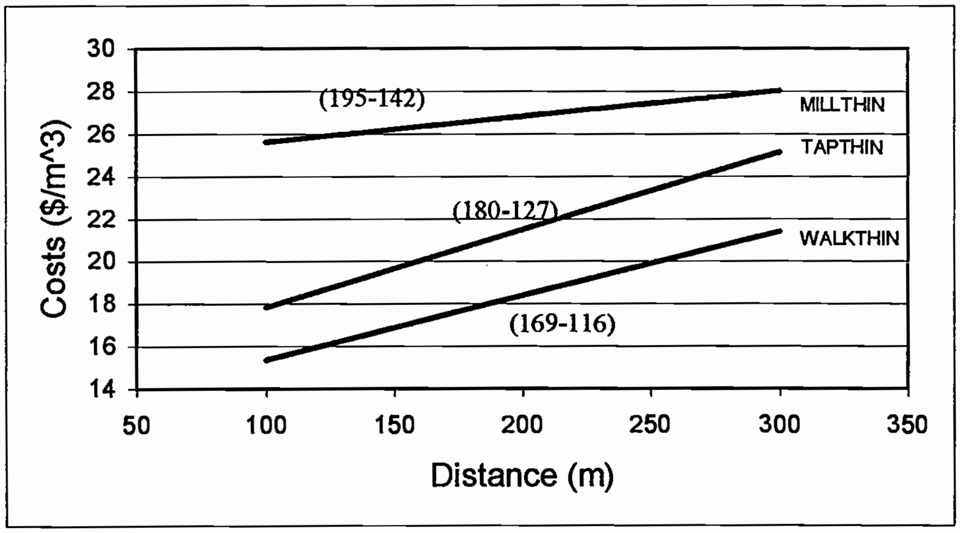


Figure 2.11. Comparison of heavy thin skyline yarding costs between sites at different distances.



Light with openings thin skyline yarding costs between sites

The slightly higher costs in Tapthin compared to Walkthin is because of the more delay and higher ownership and operating costs in the latter site. In addition distance is also an influencing factor and at the lower distance the opposite situation occurred (Figure 2.13). But the difference is not significant at average values of model variables (Figure 2.12) (Appendix Table F.4).

Figure 2.12. Comparison of light with opening thin skyline yarding costs with 95% confidence interval

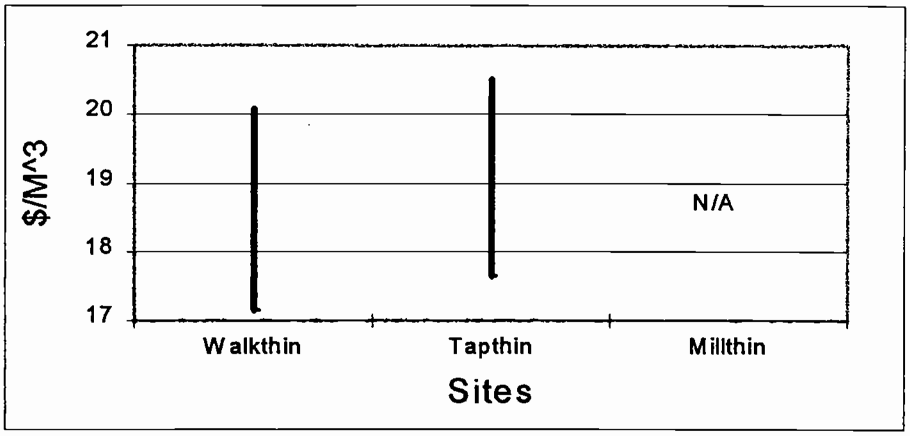
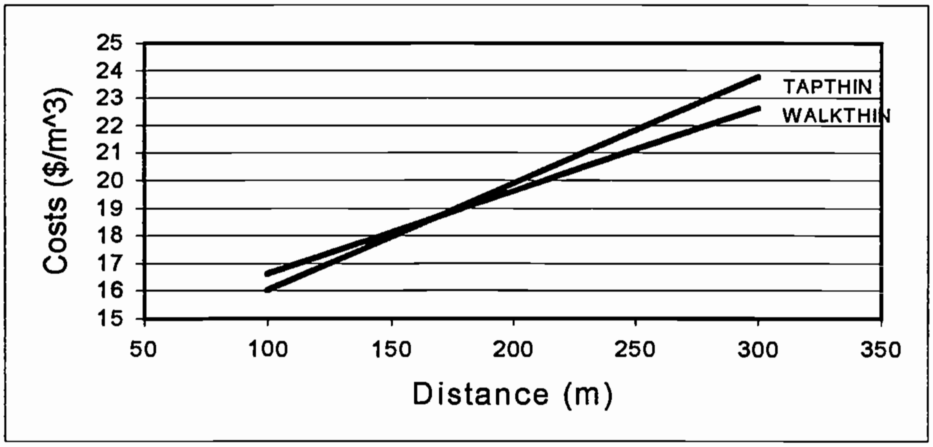


Figure 2.13. Comparison of light with opening thin skyline yarding costs between site at different distances



Light thin tractor skidding costs between sites

The costs are significantly different between Tapthin and Millthin 1 sites (Figure 2.14 and appendix Table F.11). The 4.8 min/hr. more delay, 2 min longer cycle time, and

$16.14/hr. more ownership and operating costs caused higher costs in Tapthin site (Appendix Table E.4a and E.5a).

Figure 2.14. Comparison of light thin tractor skidding cost between sites with 95% confidence interval

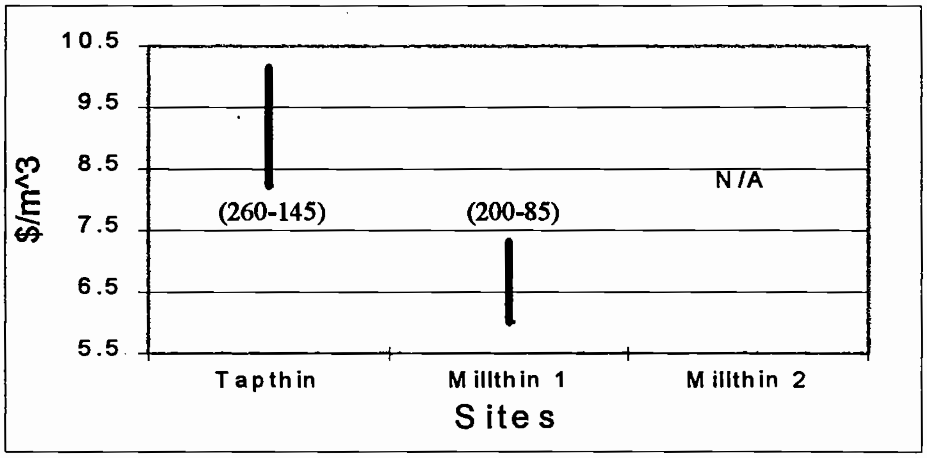
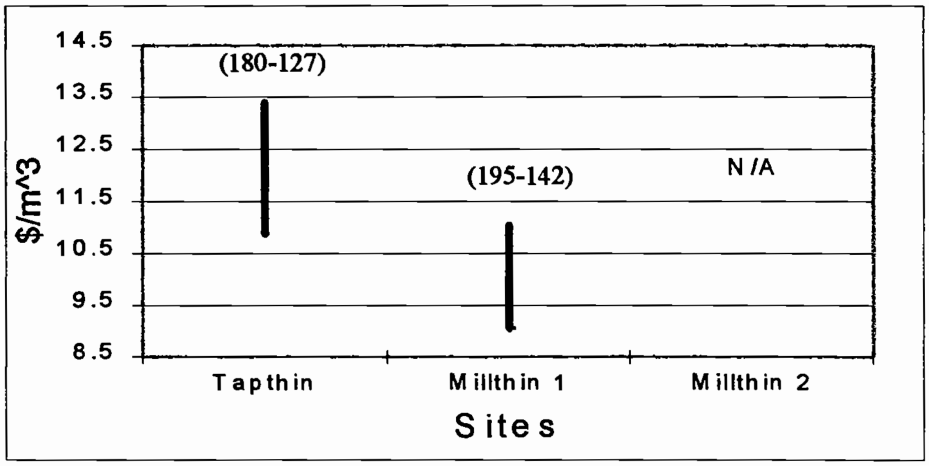


Figure 2.15. Comparison of heavy thin tractor skidding costs between sites with 95% confidence interval



Heavy thin tractor skidding costs between sites

The heavy thin costs in Tapthin is significantly higher than that of Millthin 1 site (p-value = 0.0066)(Figure 2.15 and Appendix Table F.12). Although the ownership costs are the same, 4.8 min/hr more delay and 2.9 min longer cycle time caused higher costs in Tapthin compared to Millthin 1 site (Appendix Table E.4a and E.5a).

Logging systems comparison

Light thin costs between Tapthin skyline, Tapthin tractor and Flatthin forwarder

The light thin costs for three sites are significantly different from each other both at 100 m and 300 m distance (Figure 2.16 and Appendix Table F.13).

Heavy thin costs between Tapthin skyline, Tapthin tractor and Flatthin forwarder

The heavy thin extraction costs for the three sites are significantly different from each other both at 100 m and 300 m distance (Figure 2.17).

Figure 2.16. Comparison of light thin extraction costs between Tapthin skyline, Tapthin tractor and Flatthin forwarder operations at different distances with 95% confidence interval.

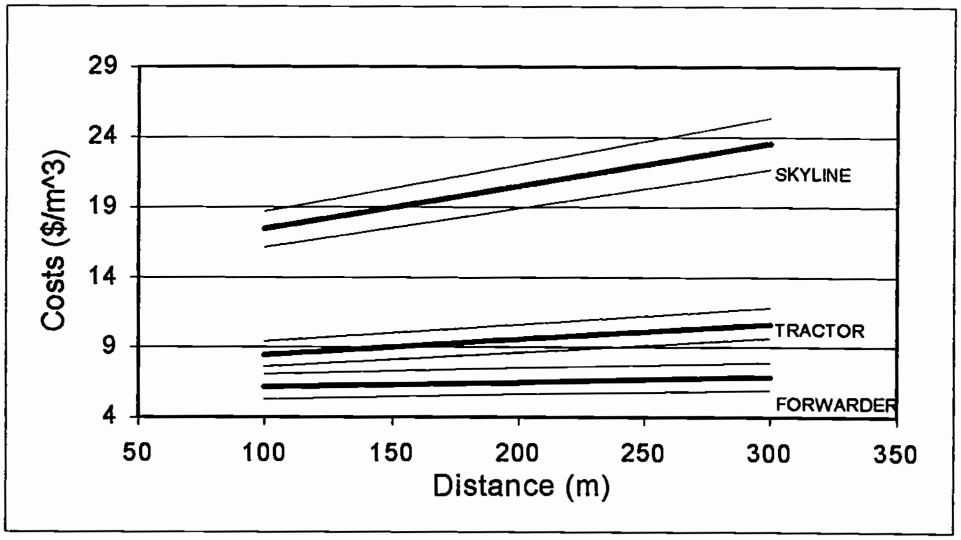
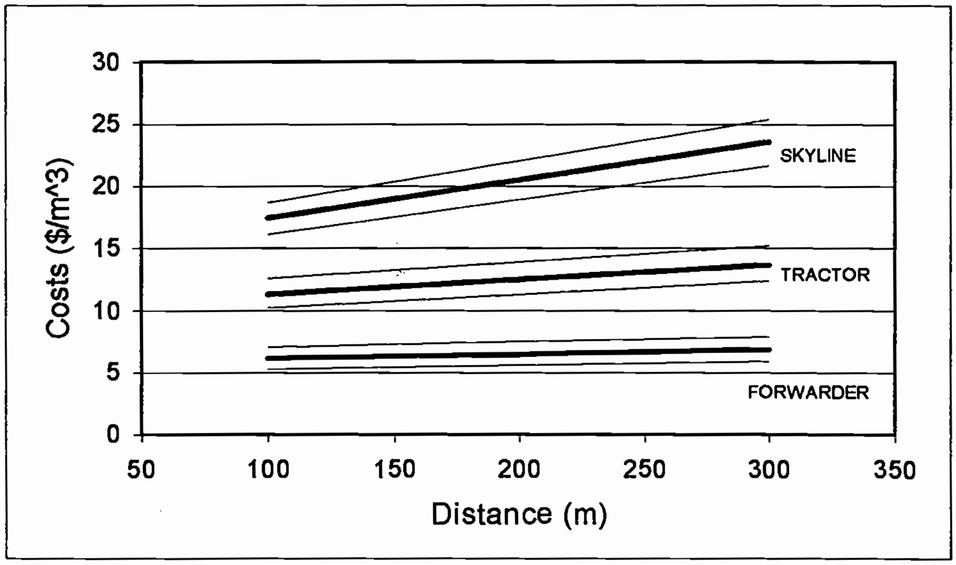


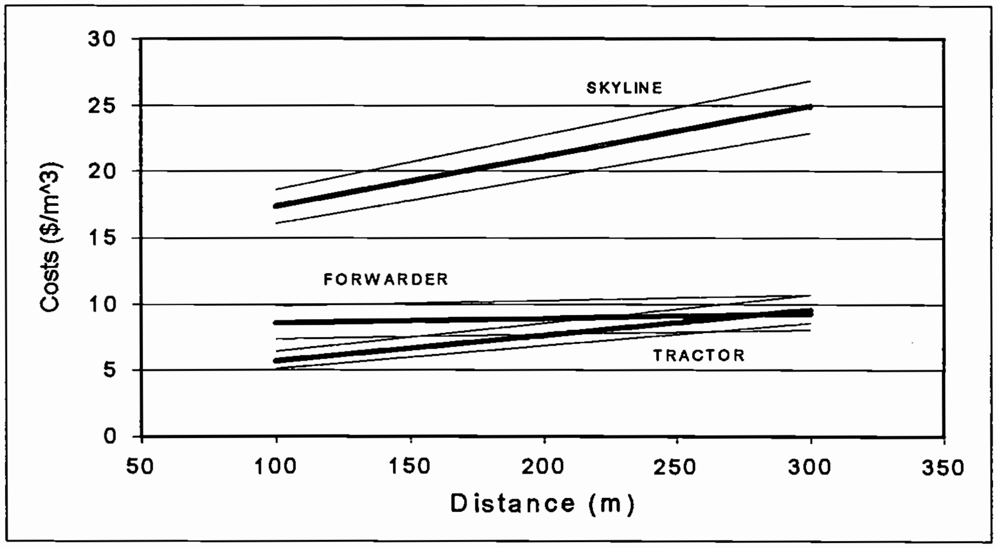
Figure 2.17. Comparison of heavy thin extraction costs between Tapthin skyline, Tapthin tractor, and Flatthin forwarder operations at different distances with 95% confidence interval.



Light with opening thin costs between Tapthin skyline, Millthin 2 tractor and Flatthin forwarder

The extraction costs for the three sites are significantly different at distance 100 m but the forwarder and tractor costs are not significantly different at distance 300 m (Figure 2.18 and Appendix Table F.14).

Figure 2.18. Comparison of light thin with opening extraction costs between Tapthin skyline, Millthin 2 tractor, and Flatthin forwarder operations at different distances with 95% confidence interval.



Flatthin harvester costs with Tapthin tractor site felling costs

The Flatthin site harvester felling and processing costs at three treatment sites are significantly different from Tapthin tractor site manual felling (Figure 2.19). It is observed that harvester costs are higher than manual felling costs in all the treatment sites. The harvester cost changes nonlinearly with DBH (Figure 2.20). At about 25 cm

DBH the harvesting costs is minimum. The manual felling cost decreases with the increase of DBH and hence with the increase of volume per cycle (Figure 2.20).

Figure 2.19. Comparison of Flatthin harvester operation costs with Tapthin tractor site felling costs with 95% confidence interval.

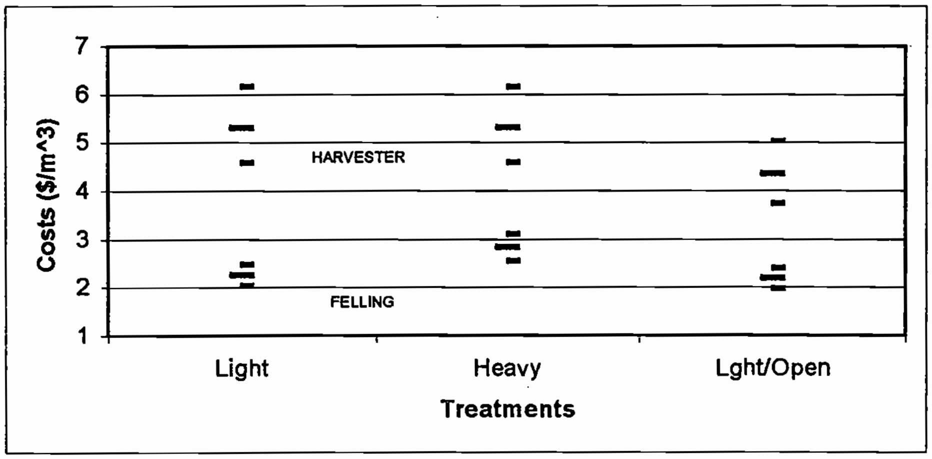
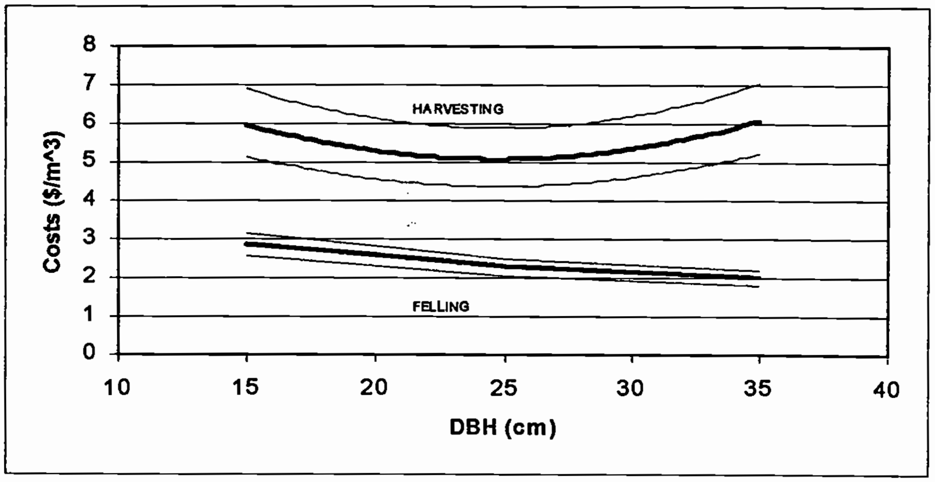


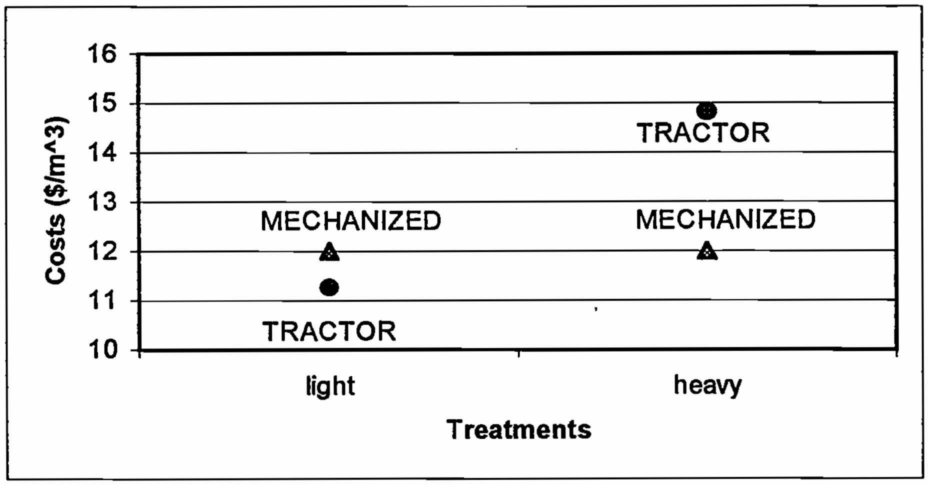
Figure 2.20. Comparison of costs between light thin harvester and light thin tractor site felling



Total harvesting costs between Tapthin tractor and Flatthin mechanized sites.

At heavy thin site total felling and extraction costs of tractor system is significantly different than total harvesting and forwarding costs of mechanized systems. Tractor costs are much higher than mechanized in heavy thin site (Figure 2.21). But at light thin site the costs of two systems are not significantly different.

Figure 2.21. Comparison of total costs between Tapthin tractor site and Flatthin mechanized site



When comparing skyline systems with skidder systems the same felling costs were assumed. When comparing the forwarder with the skidder, the felling costs are different however. The forwarder requires the bunching of the loads to be done with a harvester. A total cost comparison combines the harvester and forwarder costs. These are compared with skidder system total costs, which includes manual felling.

Since the harvester costs were higher than the felling costs, they somewhat negated the more cost effective forwarder costs. As shown in the graphs the forwarder costs are not very sensitive to the distance in comparison to skidders. The harvester costs rise rapidly as the DBH decreases. For the studied sites the tractor system costs were lower for the light thinning treatment only as shown in Figure 2.21.

Validation of regression models

Tapthin skyline yarding site

From the results of the paired t-test to verify the regression model with the reserved data, two examples are put here in Table 2.8 and Table 2.9 for the purpose of demonstration.

Table 2.8 Validation of Tapthin skyline yarding regression equation

Observation Number	Observed (min/cycle)	Predicted (min/cycle)	Residual (min/cycle)
1	3.5	3.563	-0.063
2	3.82	3.564	0.256
3	3.85	4.129	-0.279
4	4.27	4.552	-0.282
5	5.55	4.685	0.865
6	3.95	3.393	0.557
7	3.66	3.669	-0.009
8	5.55	4.116	1.434
9	3.73	3.953	-0.223
10	4.12	4.921	-0.801
11	4.87	4.912	-0.042
12	2.29	1.959	0.331
13	3.98	3.183	0.797
14	4.97	3.723	1.247
15	6.44	5.777	0.663

Table 2.8 (Continued)

16	3.88	3.293	0.587
17	4.38	4.756	-0.376
18	5.45	4.635	0.815
19	2.95	3.484	-0.534
20	3.56	3.944	-0.384
21	3.42	4.034	-0.614
22	3.51	4.511	-1.001
23	5.03	5.207	-0.177
24	3.19	3.367	-0.177
25	3.76	3.627	0.133
26	3.42	4.044	-0.624
27	4.45	4.324	0.126
28	4.69	4.606	0.084
29	4.84	4.388	0.452
30	3.31	3.042	0.268
31	4.5	5.518	-1.018
32	4.18	4.272	-0.092
33	3.18	3.511	-0.331
34	3.69	3.529	0.161
35	3.32	3.718	-0.398
36	3.65	4.016	-0.366
37	4.67	4.162	0.508
38	3.74	4.286	-0.546
39	2.96	3.449	-0.489
40	4.37	4.245	0.125
41	4.3	3.455	0.845
42	4.98	3.883	1.097
43	4.74	4.223	0.517
44	4.05	3.614	0.436
45	4.51	4.004	0.506
46	3.6	3.672	-0.072
47	4.12	4.001	0.119
48	3.68	3.899	-0.219
		Residual mean =	0.0376
		Residual standard deviation =	0.573
		t_d =	0.456

Tapthin tractor skidding site

Table 2.9 Validation of Tapthin tractor skidding regression equation

Observation Number	Observed (min/cycle)	Predicted (min/cycle)	Residual (min/cycle)
1	11.74	10.55	1.19
2	15.56	16.01	-0.45
3	10.99	10.19	0.8
4	8.41	10.41	-2
5	12.52	13.86	-1.34
6	13.71	13.9	-0.19
7	15.22	15.37	-0.15
8	12.33	14.36	-2.03
9	13.74	14.55	-0.81
10	9.16	9.85	-0.69
11	14.82	11.85	2.97
12	12.26	10.82	1.44
13	11.84	12.65	-0.81
14	12.96	10.74	2.22
15	11.16	11	0.16
16	8.97	9.52	-0.55
17	6.28	8.62	-2.34
18	12.32	8.96	3.36
19	8.36	9.82	-1.46
20	9.56	10.04	-0.48
21	13.34	11.08	2.26
22	12.09	10.3	1.79
23	8.23	9.35	-1.12
24	11.98	11.22	0.76
25	8.11	10.89	-2.78
26	10.5	10.67	-0.17
27	7.81	9.37	-1.56
28	8.33	9.29	-0.96
29	7.46	9.04	-1.58
30	7.88	8.34	-0.46
31	8.58	7.55	1.03
32	9.19	8.58	0.61
		Residual mean =	-0.104
		Residual standard deviation =	1.524
		t_d =	-0.384

In both of these tests there was no difference between the observed data, which had been reserved, and the predicted data. The validation of the regression model was done with the use of a paired t-test. The t-statistic value obtained is less than the critical values of the t-statistic at 95% level. For example the t value of paired t-test obtained in Tapthin skyline yarding and Tapthin tractor skidding sites are 0.456 (Table 2.8) and 0.384 (Table 2.9) respectively which are much less than the critical value of t = 2.0 at 95% level. That means, there is no significant difference between observed and predicted cycle time. We can conclude that the regression model does not appear to be over fitting, the random sampling procedure adopted to separate the reserved data from the data set is adequate, and the regression models fit the reserved data very well.

The models are valid only for the given range of conditions shown in the data set. The validation shows that the production comparisons made in this study are statistically sound.

SUMMARY AND CONCLUSIONS

Multiple linear regression models were developed for each of the sites (Walkthin, Tapthin, and Millthins) and for each of the logging systems (skyline, tractor and mechanized) considering all of the treatments in the site with the detailed time study data. The indicator variable approach was used to include all available treatments in building the model. Delay free skyline yarding, tractor skidding, harvesting and forwarding cycle times were regressed on the operational independent variables. The best models were selected by the stepwise forward regression method. The predicted values of the cycle time were determined using average values of the variable in the equation.

Necessary cost data for machine ownership, operating, and labor costs were collected to put in the cost diagram in order to calculate total extraction costs in each treatment. In order to compare the costs of the various scenarios, the cycle times, delays, and turn volumes were used. The corridor and landing changes were also included to give the complete extraction costs. The components of costs flowchart, the standard error term for each component, and finally the total harvesting costs in $\$/m^3$ and \$/ccf for each treatment was determined. Calculations for Table 2.7 are shown in Appendix E Tables.

The comparisons were presented in three parts. First the treatments were compared within each site and logging system. Next the sites were compared for like treatments. Lastly the logging systems were compared. A sensitivity analysis based on extraction distance was shown where appropriate.

The 95% confidence intervals of the costs were calculated for each of the scenarios. Because of the many sources of variation within the data, the confidence intervals were wide, in the plus/minus $\$2/m^3$ range. Using a t test established whether the cost differences are statistically significant.

Costs of felling in tractor sites were compared with harvesting cost of mechanized. Total costs of felling and extraction of tractor sites were determined and compared with the total costs of harvesting and forwarding.

Comparison of treatments

Using the average values of regression variables and a common delay percentage, a comparison can be made of each treatment within a site. These are shown in Table 2.7a (page 44) for seven situations. This comparison has the best standardization of conditions for this study because it was on the same site with the same equipment and crew. The yarding sites used skyline machines while the skidding sites used crawler tractors. The Tapthin yarding and the Millthin yarding showed no difference in any of the treatments. The Walkthin yarding, Tapthin skidding, and Millthin skidding found a difference between the light thinning and the other treatment(s). In Flatthin forwarding the light with opening was different than the other two treatments.

The general conclusion is that there is not a marked difference in extraction costs between treatments. The comparison is with the light thin treatment as the base. The heavy thin was more expensive in the tractor logged cases. The light with openings was more expensive in the forwarding case. In the other cases, the treatments were higher on one site and lower on another, giving inconclusive trends.

Comparison of sites

The sites were compared with each other for a given treatment. There are many sources of variation between sites, primarily differences in the equipment and crew, the logging method, the delays, corridor and landing changes, and the treatment of the fiber material. Distance variables were standardized. Although the final stocking was held constant, the volume removed per acre could not be controlled and is different between sites. Only comparisons on the skyline yarding sites were possible.

No significant difference was found between the Walkthin yarding and the Tapthin yarding on light treatments nor on light with opening treatments. All three sites were different on the heavy thin treatment. The comparison is shown in Table 2.7b (page 44). This demonstrates the range of costs that could be expected for a given treatment.

When a sensitivity analysis is done based on yarding distance the comparisons are more evident. Figures 2.9 and 2.11 showed how the light treatments coincide. Figure 2.10 showed how the heavy treatments costs are clearly separated between sites.

On the tractor skidding sites the light and heavy were both significantly different between the two sites as shown in Table 2.7c (page 44). The Tapthin site had consistently higher costs.

Comparison of logging systems

The system comparisons are shown graphically in Figures 2.16, 2.17 and 2.18. A comparison of skyline and tractor systems is shown for each treatment on the Tapthin site. The skyline yarding costs are approximately double the tractor skidding costs. The skyline costs are more sensitive to yarding distance, again increasing at a higher rate than skidding as the distance increases.

A comparison between the tractor and the forwarder can only be inferred. The mechanized system forwarding was only done on the Flatthin site. In addition the felling costs must also be included since the forwarding only works in combination with a harvester which bunches the wood along the skid trails prior to forwarding.

The harvester cost is much higher than the manual felling which accompanies the skidder operation as shown in Figure 2.19. So although the forwarder has a cheaper cost than the tractor skidding for all treatments and over most of the extraction distances range as shown in Figures 2.16, 2.17 and 2.18, adding in the harvester cost negates the cost advantage. A comparison of this total cost is shown in Figure 2.21 for the light and heavy treatments. The two systems do not have statistically significant differences that are consistent.

The harvester cost changes nonlinearly with DBH as shown in Figure 2.20 on page 56. At about 25 cm DBH the harvesting cost is minimum.

Relative differences among treatments, sites, and systems

The most dramatic and consistent differences in the study were between the skyline yarding costs and the tractor skidding. Under all conditions the skyline was far more expensive. As yarding distance increased, the gap between costs widens even more.

The mechanized system has costs similar to tractor skidding at the study average distances. When distance increases the harvester/forwarder system becomes cheaper than the felling/skidding system.

Differences between sites were clear for skidding. The costs for skyline yarding sites tended to not be significantly different from each other when compared for the same treatment. This demonstrates that a range of costs can be expected based on site specific operating conditions.

The experimental design of the study standardized conditions for comparing among treatments. In about 1/2 of the parings a cost difference was established between treatments. Surprisingly, the light thin with openings tended to be more expensive than the base case of light thin.

In two of six of the parings the heavy thin was more expensive than the base case of light thin. In general the costs of heavy thin and light with openings were similar.

It appears that the cost of the thinning treatments need not be a major consideration when deciding on wildlife habitat manipulation. The most dramatic impact will be caused by the steepness of the slope dictating whether skyline yarding is required.

Importance of confidence intervals and sensitivity analysis

The confidence intervals allowed us to test if differences in costs were significant. These intervals were calculated from the unexplained variation in cycle times, cycle volumes, and delay percentages. This is often omitted in reports on production and costs. In general the confidence intervals showed that the differences in costs were not statistically significant.

Conclusions from this study are only valid within the range of conditions studied. Sensitivity analysis showed that extraction distance and piece size have a dramatic effect on the costs. When making comparisons these variables must be standardized. A sensitivity graph should be shown which reflects the changes in costs at different distance and DBH.

Chapter 3

DELAY ANALYSIS IN TIMBER HARVEST OPERATIONS

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INTRODUCTION

A delay is defined as any work interruption that is not part of a productive work activity. Delays consume 20% to 30% of the work day and have a major effect on the cost of logging. The common categories into which delays are grouped are operational, repair, personal, and mechanical. Lunch breaks and routine servicing of equipment are considered out-of-shift activities and therefore not delays. Landing and road changes are usually prorated against the entire unit rather than on a per cycle basis.

Delay information is gathered in four main ways. First, detailed time studies usually record all delays, especially delays less than 10 minutes. These delays are operational type such as resetting chokers. Second, shift level studies record only delays lasting 10 minutes or more. These will typically be mechanical breakdowns. Third, activity sampling is done to establish machine interference and wait time. The percentage of various types of delays is often an outcome of activity sampling. Fourth, a variety of mechanical and /or electrical recording devices are used to chart the power used by equipment. This can be translated into work and non-work periods. In this paper only the first two ways will be used: detailed time studies records for small delay analysis and shift level records for large delay analysis.

Delays are used in equipment evaluation, product costing, and comparisons between logging methods. Equipment effectiveness is measured by the ratio:

$$\frac{\left(T_{total} - T_{delay}\right)}{T_{total}} = Utilization\%$$

or, $$\left(1-\frac{T_{delay}}{T_{total}}\right)=Utilization\%$$

Where: T_{total} = total time

T_{delay} = delay time

For the purpose of logging cost calculation, Utilization % is converted into an Effective hour with units of minutes:

Effective hour = (Utilization %)(60 min/hr)

Production per hour and costs per hour are reported either with or without delays. If the production and cost include delays it is on a scheduled machine hour (smh) basis. If the production and cost are delay-free then they are on a productive machine hour (pmh) basis. The scheduled machine hour basis is the preferred method in most cases because it reflects the production and cost that will occur.

This comprehensive analysis of delays will aid in production and cost analysis in two ways. First, if we determine that the delay percentage is not treatment specific, we can use a common percentage for all treatments. We then can compare the difference between the treatments' cycles per hour on the cycle times alone. Secondly, if we can establish that the Poisson and exponential distributions are appropriate we can determine the length of study needed in order to reasonably estimate the delay percentages.

For short studies, the delay percentages often appear to be different between treatments. If a longer study is taken, it may be evident that there is no delay percentage difference between the treatments.

The comparison of the percent of delays in various categories is an important part of comparing logging methods. This chapter will focus on the analysis of both large and small delays.

Literature review

Almost no research has been published on detailed harvesting delay analysis using individual categories, delay frequencies, and delay duration. The typical delay analysis was done by lumping the delays all together and showing the percentage of delay.

Dykstra (1976) demonstrated that the predictions of total harvesting costs in each case can be more accurate if downtime is considered by individual category rather than lumping them all together. He reported that this should result in more accurate estimates of total yarding cost. He also emphasized an understanding of the factors that influence the delays.

Tufts, et al. (1982) did two research studies: one on frequency of failure for forest harvesting equipment and the second one on the effect of reliability and maintainability on equipment availability. In the first one, time between failure and time to repair distributions for three forest equipment were presented. He found considerable variability among machines of the same type. In the second study he concluded that machine availability increases with increasing time between failures but at a decreasing rate, approximating the classic "diminishing returns" curve. He found that as time to repair and delay time decrease availability increases at a constant rate.

Boyd (1973) demonstrated that reducing downtime will not necessarily reduce the costs of wood produced. The benefits of increased availability must be greater than the costs of achieving reduced down-time.

Mellgren (1989) explained why it had been difficult to get high mechanical availability with multi-function machines. Simplified reliability theory was applied to demonstrate the relationship between mean time between failures of components and mechanical availability for machines of various complexities. He suggested that the design engineers balance between high reliability and low weight/low cost machines.

A detailed description of machine performance methods was done by Thompson (1988). He classified cable skidder time elements into (1) productive, (2) mechanical delays, such as, refuel, maintenance, repair, wait for repair, warm-up, and (3) non-mechanical delays, such as, breaks, discussion, drop hanger, stuck, injury. He also described time for cycle elements: some are repetitive (hook, winch), some are periodic (routine maintenance, breaks), and others occur at random (delays, breakdown).

Theory

Delays have two components: the frequency at which they occur, and the duration for which they last. Delays are mostly randomly occurring events with many causes. These causes may be mechanical wear, human foibles, or the effect of unpredictable site conditions. The classical distributions which describe such randomness are the Poisson distribution of frequency and the exponential distribution for duration.

The Poisson distribution is a discrete (0, 1, 2, 3, . . .). For example it can describe the delays per cycle. The exponential is a continuous distribution which can describe minutes per delay. Both of these curves have distinctive shapes when graphed. The Normal curve may be tried as the default curve if the Poisson or exponential fail the goodness of fit tests. The formulae for these distributions are as follows:

Poisson distribution

$$P(x) = \frac{\beta^{x} e^{-\beta}}{x!} \qquad x = 0, 1, 2, \ldots\ldots$$

$$E(x) = \beta \qquad \mathrm{var}(x) = \beta$$

After calculating β (mean) of Poisson it can be treated as variance (σ^2).

Exponential distribution

$$f(x) = \beta e^{-\beta x} \qquad x \geq 0$$

$$E(x) = \frac{1}{\beta} \qquad \mathrm{var}(x) = \frac{1}{\beta^{2}}$$

Hence, the variance is the square of the mean of exponential.

Normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(x-\mu)^{2}/2\sigma^{2}} \; \textit{all real } x$$

$$E(x) = \mu \qquad \mathrm{var}(x) = \sigma^{2}$$

The spreadsheet command for cumulative distribution function for the exponential curve is:

F(x) = 1-@exp(-x/mean)

where: x = duration

$$\text{mean} = \frac{\sum \text{delays duration}}{\text{total number of delays}}$$

Statistical tools

The statistical tools for analyzing the delay frequency and delay duration are explained in this section. The t-test, Chi-square test, and Kolmogorov-Smirnov (K-S) test are useful to test the differences between treatments. The distribution of delay frequency and duration are tested with theoretical curves.

t-test

The means of the delay frequencies (delay/cycle) and the delay duration (minute/delay) can be compared between the treatments (light, heavy and light with openings) by using the t-test. The t-ratio is often valid even if the population distributions are non-normal or the standard deviations unequal (Ramsy, et al., 1994). The formula for comparison of unequal sample sizes is as follows:

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 + n_2 - 2)}}$$

where: S_p = Pooled Standard Deviation
n_1 and n_2 = sample sizes of two treatments
s_1 and s_2 = standard deviations of two samples
$(n_1 + n_2 - 2)$ = degree of freedom *(df)*

$$SE_{(\overline{X_1}-\overline{X_2})} = S_p\sqrt{\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}$$

where: X_1 and X_2 = estimates of means of two samples
$SE_{(X1-X2)}$ = standard error of estimates

$$t\_stat = \frac{\left(\overline{X_1} - \overline{X_2}\right)}{SE_{(\overline{X_1}-\overline{X_2})}}$$

Test Ho : no difference

$$t\_stat < t_{df(1-\alpha/2)}$$

where: (1-α/2) is the confidence level at 95%

95% confidence interval

$$\left(\overline{X_1} - \overline{X_2}\right) \pm t_{df(1-\alpha/2)} SE_{(\overline{X_1}-\overline{X_2})}$$

Chi-square test

The χ^2 (Chi-square) distribution, when associated with discrete data, is usually in conjunction with a test for goodness of fit. The test criterion is

$$\chi^2 = \sum \frac{(theoretical_i - observed_i)^2}{theoretical_i}$$

where: *i* = number of cells in *r*-by-*k* table, the table in which observed frequencies are arranged in *r* rows and *k* columns.

The above formula can more specifically be expressed as:

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{k} \frac{(theoretical_{ij} - observed_{ij})^2}{theoretical_{ij}}$$

We reject the null hypothesis if the value of this statistic exceeds $\chi^2_{\alpha=0.05}$ with (r-1)(k-1) degrees of freedom. In this formula the sum is taken over all cells in the classification table. Observed refers to the numbers observed in the cells; expected refers to the average numbers or expected values when the hypothesis is true, that is, to the theoretical values.

K-S test

The Kolmogorov-Smirnov (K-S) tests are nonparametric tests for differences between two cumulative distributions (Miller, 1965). The one-sample test concerns the agreement between an observed cumulative distribution of sample values and a specified continuous distribution function; thus it is a test of goodness of fit. In other words, the one-sample test is based on the maximum absolute difference between the values of the cumulative distribution of a random sample of size n and a specified theoretical distribution.

Justification of the study

When comparing systems, the difference in delay percentages between systems has an effect on cost of the same magnitude as the differences in production between the systems. Delays may vary between logging systems (skyline yarding, ground based tractor logging and ground based mechanized) and between treatments (light, heavy and light with gap) in each logging system. Hence analysis of delay is an important component of the system costs comparison. When considering replacing an old machine with a new one, delay analysis is necessary because the complexity of the new system might cause it to have higher delays than the old one.

Hypothesis

Treatment differences in delays can be found using standard t test, Chi-square test, and K-S test.

Objectives of the study

1. To find a technique to test the differences between treatment means of delays
2. To check fitness of observed delay distribution with theoretical curves.

METHODS AND PROCEDURE

The field study which is the source of delay data is a part of the multidisciplinary joint project undertaken by the Willamette National Forests and Oregon State University on managing young conifer stands for multiple resources in the Central Western Cascades of Oregon.

This part of the study is concentrated on the comparative analysis of harvesting production and costs. The study consists of four silvicultural treatments (Kellogg, et al., 1997): (1) control (no thinning), with approximately 618 tph (250 tpa), (2) light thinning, leaving 247-272 residual tph (100-110 tpa), (3) heavy thinning, leaving 124-136 residual tph (50-55 tpa), and (4) light thinning, with small opening (0.20 hectare (0.5 acre) opening in 20% of the stand) followed by under planting with a mixture of Douglas-fir, western hemlock, and western redcedar. The sites include units from five thinning sales (Walkthin, Tapthin, Millthin 1 and Millthin 2, and Flatthin), which are located in three United States Forest Service (USFS) ranger districts: Oakridge, McKenzie, and Blue River

The three different logging systems used in thinning were small skyline yarding system, tractor/skidder ground based system, and a mechanized cut-to-length (short wood) harvester-forwarder ground based system. The types and specifications of logging equipment and the method used are shown in Appendix C (Kellogg, et al., 1997 and 1998).

The two data collection methods used in this study were shift level study and detailed time study.

Shift level data records daily summaries of number of turns, piece count, hours worked, crew size, and major delays (over 10 minutes). A sample shift level skyline yarding recording form is shown in Appendix G-1. One person was chosen from the felling and yarding crew to be responsible for filling out the forms daily. One person from the crew also records the scale ticket information on the log trucks. Road and landing change information is recorded to the nearest 10 minutes (Kellogg et al., 1997). This study is conducted over as long a period of time as the harvesting lasts.

The detailed time study was done by handheld computer. The data were then down loaded to a personal computer spreadsheet for screening and data management. Two researchers are engaged for collecting all of the data. The study usually lasts a week or less. Turn times are recorded along with associated variables like yarding distance, lateral distance, carriage height, etc. Both small delays (less than 10 minutes) and large delays (over 10 minutes) were recorded.

Each detailed time study delay was categorized by code. The skyline yarding delay codes are shown below:

Code – Name of delay

Operational:

5 – Landing delays
10 – Reposition carriage/resetting chokers
15 – Planning
20 – felling and bucking
25 – Rigging cuts
30 – Pulled anchor stump or tailtree/stump tailhold
35 – Yarder adjustment/wait yarder
40 – Line/rigging adjustments and /or checks
45 – Wait loader
50 – Wait chaser
55 – Put on/take off extra chokers
60 – Transfer of rigging, equipment, powersaws, lunches along skyline
65 – Clear corridor obstacles with carriage
70 – Fuel
75 – Pick up logs
80 – Miscellaneous

Repair:

100 – Yarder repair
110 – Loader repair
120 – Line/rigging repair
130 – Block repair
140 – Miscellaneous

Personal:

200 – Food, water
210 – Discussion
220 – Miscellaneous

Non-productive activities:

300 – Researchers in way
400 - Miscellaneous

There were so few delays occurring in each of the categories that it was difficult to get a sufficient sample size in each category. Depending on the number of observation against each delay code, the delay data were combined for analysis in this paper as follows:

<u>Code</u> – <u>Name of delay</u>

5 – Landing delays
10 – Reposition carriage/resetting chokers
40 – Line/rigging adjustments and /or checks
Other – Other remaining delays.

The shift level delays were categorized into maintenance, mechanical, personal, and miscellaneous. These delays are most likely independent of the logging methods (treatments) being used. For example the breakdown of harvester head chain is not dependent on any treatment. Also, for example, maintenance and mechanical delays were associated with the logging equipment rather than the method. The age and condition of the machinery influenced how many large delays occurred. The work habits of the crew affected the personal delays. Because the large delays are not likely to be affected by variations in the logging treatments, all large delays were combined together for further analysis.

The walkthin skyline yarding site was randomly chosen for demonstration in this paper.

Analysis procedure

There are several ways to proceed with delay analysis and curve fitting. We will demonstrate each of these in turn. The delay analysis should usually be done in this order.

1. Justifying theoretically
2. Comparing the expected relationship between the mean and the standard deviation of the data.
3. Comparing plots of the observed and theoretical curves.
4. Testing statistically with t-test, Chi-squared, and K-S.

Delays can be viewed as failures in the system. The distribution of failures has been extensively studied and reported in reliability literature. If the failures are random occurrences, there is good reason to believe that the frequency of occurrence will have a Poisson distribution. If the time to remedy the delay is also somewhat random, then their duration will follow the exponential distribution. In skyline thinning, both the small and large delays are probably caused by random events. Since the repair is largely human paced, the repair time will have a large variability and may be exponentially distributed.

Comparison of means and standard deviations

The mean equals the variance in the Poisson distribution. The mean equals the standard deviation in the exponential distribution. The means and variances can easily be calculated from the observed data. If they meet these criteria, then further comparison is warranted.

Table 3.1 shows that the exponential distribution is a good candidate for the fitting of the observed duration of small delay data. However the Poisson fit of frequency is questionable. This result warrants further comprehensive analysis.

Table 3.1. Comparison of means and standard deviations of small delay data

	Mean	Std. Dev. Observed	Std. Dev. Theoretical	Conclusion
Frequency (delay/cycle)	0.601	0.257	0.775	not same as Poisson
Duration (min./delay)	0.904	0.894	0.904	similar to exponential

Plots of small delays

The Poisson and exponential curves both have very distinctive shapes. Plots of the observed data will reveal whether the appropriate shapes exist. These plots can be done using spreadsheet graphical functions.

The Figure 3.2 shows the delays per cycle compared with a Poisson curve having the same mean. The fit appears close enough to warrant the statistical tests.

The duration plot of the observed data as will be shown later resembles the exponential distribution which has the same mean time per delay. These distributions appear to have the correct shape. Therefore we will perform the statistical tests.

Most computer statistical software packages will do the goodness of fit tests using either the Chi-squared or the K-S.

Statistical tests

Having completed the somewhat subjective qualitative comparison we now proceed to do the statistical tests.

First, a t-test was performed to check if there is any differences between the small delays means of treatments for both delays frequency (number of delays/cycle) and delay duration (minutes/delay). Test was done at 95% confidence level. The data were then combined if there was no significant differences between the treatments.

A Chi-square test with contingency table was done with small delays for delay frequency, delay duration, and delay category distribution. For small delays this test was done for comparing frequency, duration and code-wise distribution between the treatments. For large delays chi-square test was done for delay frequency and delay duration. The objective of this test in large delays, was to check the fit of observed curve with the theoretical curves.

For both small and large delays, the delay frequency was tested against a Poisson theoretical distribution curve. In the same way, delay duration was tested against the theoretical exponential distribution curve. For confirming these distributions the K-S test was performed for both cases. The K-S test was done by calculating cumulative values of observed and theoretical frequencies and duration. The K-S values (the difference between theoretical and observed) thus obtained were compared with the critical values of K-S using statistical tables.

ANALYSIS AND RESULTS

The t-test was performed for comparing delay frequency and duration means among treatments. Chi-square test was done for comparing delay frequency, duration, and delay category distributions, and K-S test was performed for conforming fitness of observed distribution with theoretical curves. The following sections show all tests and their results.

Small Delays

t_test

Mean delay frequency (delay/cycle) and mean delay duration (minute/delay) were compared between the treatments using the t-test. The test was done at 95% confidence level. The mean delay frequency and delay duration, standard deviations and sample sizes of three treatment sites are shown in Table 3.2 and 3.3.

Table 3.2. Average small delay frequency mean, standard deviation and sample size in each treatment.

	Light	Heavy	Light with opening
Mean (x), delay/cycle	0.600	0.603	0.604
Std. Dev.(s), delay/cycle	0.300	0.229	0.232
Sample Size (n)	28	25	25

Table 3.3. Average delay duration mean, standard deviation and sample size in each treatment

	Light	Heavy	Light with opening
Mean (x), minute/delay	0.830	0.670	1.240
Std. Dev.(s), minute/delay	0.740	0.550	1.190
Sample Size (n)	28	25	25

The stepwise comparison of delay frequency and duration by t-test are shown in Tables 3.4 and 3.5 respectively.

Table 3.4. Comparison of delay frequencies between treatments

Treatments	S_p	SE	t_stat	$t_{df(1-\alpha/2)}$	Result
Light vs. Heavy	0.269	0.074	0.04	2.01	0.04<2.01
Light vs.Light/Opening	0.073	0.02	0.20	2.01	0.20<2.01
Heavy vs.Light/Opening	0.230	0.065	0.015	2.01	0.015<2.01

Table 3.5. Comparison of delay duration between treatments

Treatments	S_p	SE	t_stat	$t_{df(1-\alpha/2)}$	Result
Light vs.Heavy	0.657	0.181	0.884	2.01	0.884<2.01
Light vs.Light/Opening	0.978	0.269	1.52	2.01	1.52<2.01
Heavy vs.Light/Opening	0.926	0.262	2.17	2.01	2.17>2.01

Chi-square test with contingency table

Chi-square test for frequency distribution

Table 3.6a. Observed number of cycles with respective frequencies in different treatments

Number of Delays/Cycle	Light	Heavy	Light with Opening	Combined
0	149	152	184	485
1	130	137	130	397
2 or more	21	27	37	85
Total	300	316	351	967

Table 3.6b. Theoretical number of cycles with respective frequencies in different Treatments

Number of Delays/Cycle	Light	Heavy	Light with Opening	Combined
0	150.45	158.47	176.03	50.15%
1	123.15	129.72	144.08	41.05%
2 or more	26.37	27.78	30.85	8.79%
Total	300	316	351	100%

For frequency, Chi-square, $\chi^2 = \frac{(150.45-149)^2}{150.45} + ... + \frac{(30.85-37)^2}{30.85}$

or, $\chi^2 = 5.145 \langle \chi^2_{\alpha=0.05} = 9.488$, from Table V (Miller, 1965)

Chi-square test for duration distribution

Table 3.7a. Observed number of cycles with respective duration in different Treatments

Time (cmin)	Light	Heavy	Light with Opening	Combined
20	61	74	52	187
40	37	52	36	125
60	27	18	25	70
80	9	12	20	41
Other	42	35	79	156
Total	176	191	212	579

Table 3.7b. Theoretical number of cycles with respective duration in different treatments

Time (cmin)	Light	heavy	Light with Opening	Combined
20	56.83	61.67	68.45	32.29%
40	38.00	41.24	45.77	21.59%
60	21.28	23.09	25.63	12.09%
80	12.46	13.52	15.01	7.08%
Other	47.41	51.45	57.11	26.94%
Total	176	191	212	100%

For duration, Chi-square, $\chi^2 = \frac{(56.83-61)^2}{56.83} + \ldots\ldots\ldots\ldots + \frac{(57.11-79)^2}{57.11}$

or, $\chi^2 = 31.313 \rangle \chi^2_{\alpha=0.05} = 15.507$, from Table V (Miller, 1965).

Chi-square test for category distribution

Table 3.8a. Observed number of cycles with respective codes in different Treatments

Code	Light	Heavy	Light with Opening	Combined
5	8	19	25	52
10	117	144	105	366
40	18	15	9	42
Other	33	13	73	119
Total	176	191	212	579

Table 3.8b. Theoretical number of cycles with respective codes in different Treatments

Code	Light	Heavy	Light with Opening	Combined
5	15.80	17.15	19.04	8.98%
10	111.25	120.73	134.00	63.21%
40	12.76	13.85	15.37	7.25%
Other	36.17	39.25	43.57	20.55%
Total	176	191	212	100%

For code-wise distribution, Chi-square, $\chi^2 = \frac{(15.80-8)^2}{15.80} + \ldots\ldots\ldots + \frac{(43.57-73)^2}{43.57}$

or, $\chi^2 = 59.57 \rangle \chi^2_{\alpha=0.05} = 12.592$, from Table V (Miller, 1965).

K-S test

Poisson distribution of delay frequency

Light Treatment

Total number of cycles = 300

Number of cycles with delays = 176

Delays/cycle = 176/300 = 0.59

Table 3.9a. K-S table for frequency

Delay/Cycle	Observed (cumulative)	Theoretical (cumulative)	Difference (Δ)
0	0.496	0.555	0.059
1	0.930	0.881	0.049
2	0.987	0.978	0.009
3	1.000	0.997	0.003

From table IX (Miller, 1965), the differences are < 0.24, showing a very good fit of observed curve with the theoretical curve.

Light with Openings Treatment

Total number of cycles = 351

Number of cycles with delays = 167

Delays/cycle = 167/351 = 0.476

Table 3.9b. K-S table for frequency

Delay/Cycle	Observed (cumulative)	Theoretical (cumulative)	Difference (Δ)
0	0.524	0.619	0.059
1	0.895	0.916	0.021
2	0.977	0.987	0.010
3	0.997	0.998	0.001
4	1.000	1.000	0.000

from table IX (Miller, 1965), the differences are < 0.24, showing a very good fit of observed curve with the theoretical curve.

Heavy Treatment

Total number of cycles = 316

Number of cycles with delays = 164

Delays/cycle = 164/316 = 0.52

Table 3.9c. K-S table for frequency

Delay/Cycle	Observed (cumulative)	Theoretical (cumulative)	Difference (Δ)
0	0.481	0.595	0.114
1	0.915	0.904	0.011
2	0.987	0.984	0.003
3	1.000	0.998	0.002

from table IX (Miller, 1965), the differences are < 0.24, showing a very good fit of observed curve with the theoretical curve.

Combined

The delay frequency data of the three treatments were combined and analyzed as follows:

Total number of cycles = 967

Number of cycles with delays = 507

∴ Delays/cycle = 507/967 = 0.524

Table 3.10. K-S table for frequency

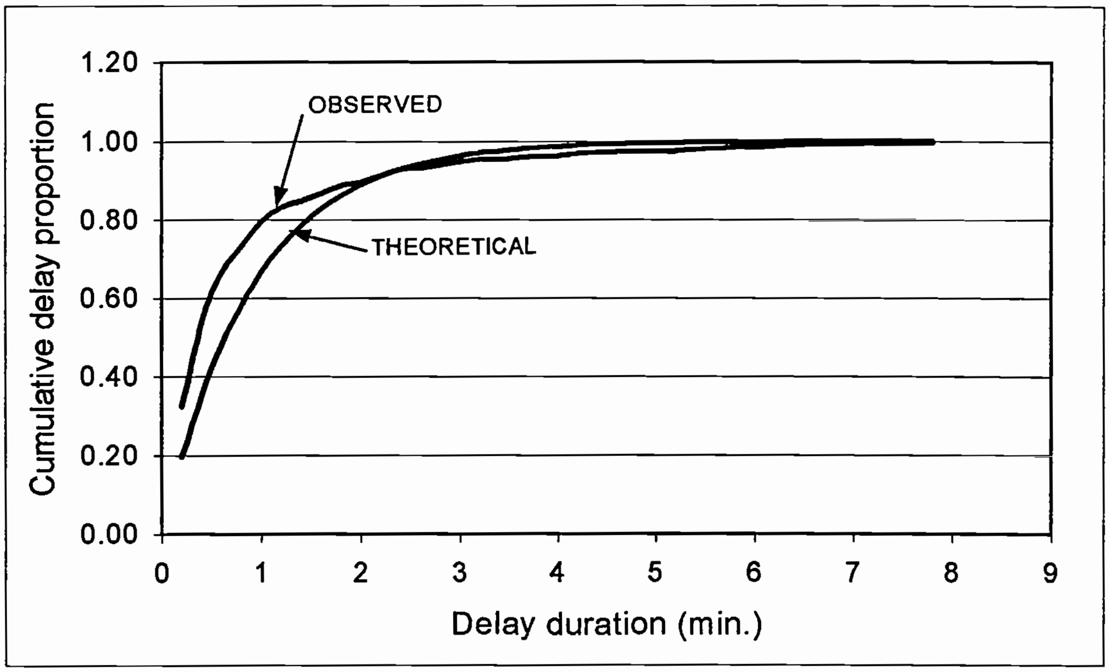
Delays/Cycle	Observed (cumulative)	Theoretical (cumulative)	Difference (Δ)
0	0.501	0.593	0.092
1	0.912	0.902	-0.010
2	0.983	0.984	0.001
3	1.000	0.998	-0.002

From table IX (Miller, 1965), the differences are < 0.24, showing a very good fit of observed curve with the theoretical Poisson curve.

K-S test for small delay duration

The delay duration data of the three treatments were combined for performing the K-S test to see specifically if there is any difference between actual and theoretical cumulative exponential curves. The result of the test is shown in Figure 3.1.

Figure 3.1. K-S test for small delay duration



The observed curve is close to theoretical K-S curve (Figure 3.1). The maximum difference is 0.19, at duration 0.40 minute, which is less than 0.24, the limiting value to be compared with the theoretical curve.

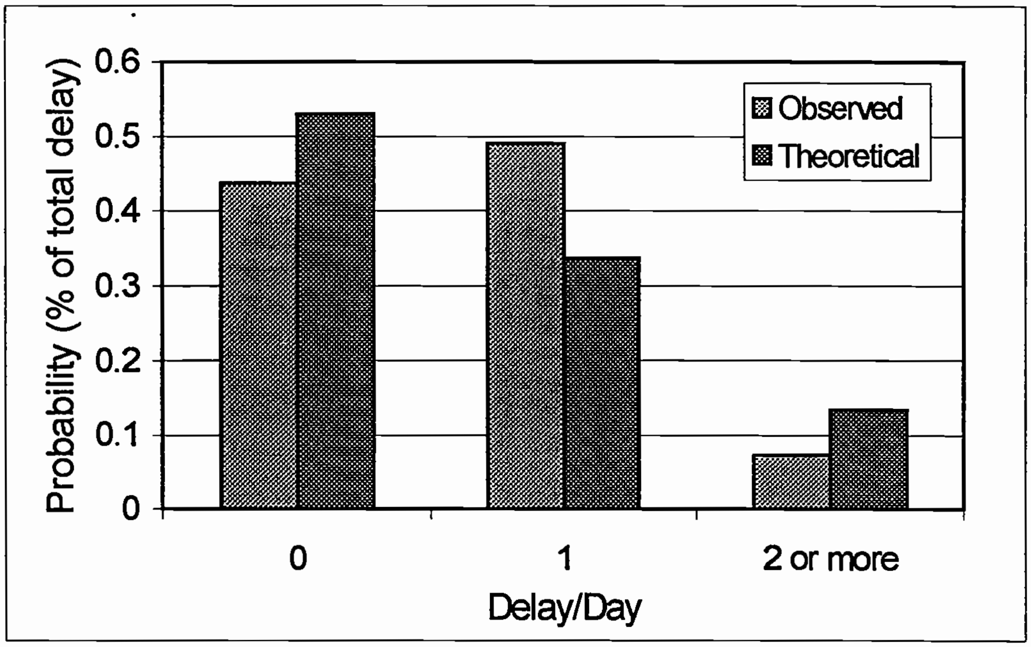
Large Delays

The large delays are often equipment specific. Delay occurrences are not generally dependent on treatments. For that reason large delay data in all treatments are combined for analysis. No tests were done comparing treatment means, comparing treatment distributions, or treatment codes using the Chi-square tests. So the only tests will be a goodness-of-fit with theoretical curves.

Poisson distribution of large delay frequency

The distribution of observed delay frequency was drawn in a graph to see if its general shape matched the theoretical Poisson curve (Figure 3.2). The observed data distribution is similar, so a Chi-square test and a K-S test were done.

Figure 3.2. Poisson distribution of large delay frequency



Chi-square test and K-S test for large delay frequency

Table 3.11a. Number of days and delays in different delay frequencies

Delay/Day	# of Days	# of Delays
0	90	0
1	101	101
2	15	30
Total	206	131

Total number of days = 206

Total number of delays = 131

$\therefore$ Delays/Day = 131/206 = 0.636

Table 3.11b. Table of Chi-square test

Delays/Day	Observed	Theoretical	Chi-square(χ^2)
0	90 (0.437)	109 (0.529)	3.31
1	101 (0.490)	69.4 (0.337)	14.39
2	15 (0.073)	27.6 (0.134)	5.75
Total	206 (1.000)	206 (1.000)	23.45

The column in parenthesis in the above table can be obtained either from Table II (Miller,1965) for mean frequency of 0.636 delay/day or by using the Poisson formula p(x)

$= \mu^x e^{-\mu} / x!$. The high Chi-square value (23.45) shows that the observed curve does not fit with theoretical curve.

K-S test for large delay frequency

Table 3.12. K-S table for frequency

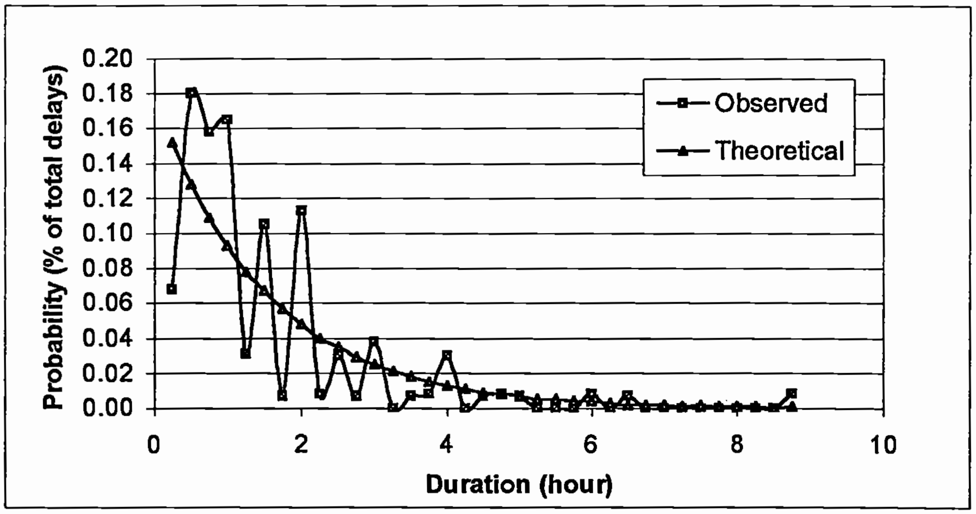
Delays/Day	Observed (cumulative)	Theoretical (cumulative)	Difference
0	90/206=0.437	0.529	0.092
1	191/206=0.927	0.866	-0.061
2	206/206=1.000	1.000	0.000

The small differences show a very good fit of observed curve with the theoretical curve. From the cumulative distribution of the K-S test, the maximum difference between actual and theoretical distribution is 0.092 at the frequency of 0 delay/day, which is less than the limiting value for fitting with the theoretical Poisson curve. We were not able to reject the null hypothesis that the frequency was not Poisson.

Exponential distribution of large delay duration

The exponential distribution of observed delay duration is shown against theoretical exponential distribution (Figure 3.3). The observed data is similar to the theoretical curve so a K-S test will be performed on the cumulative distributions.

Figure 3.3. Exponential distribution of large delay duration



The small differences show a good fit of observed curve with theoretical curve Table 3.13). The maximum difference between these two cumulative curves is 0.095 corresponding to the duration 2.00 hours, which is within the limiting value for fit with theoretical curve. That means, the observed large delay duration distribution is exponential.

K-S test for large delay duration

Table 3.13. K-S table for large delay duration

Duration (hour)	Number of delay	Cumulative delay	Observed	Theoretical	K-S
0.25	9	9	0.068	0.152	0.084
0.50	24	33	0.248	0.280	0.032
0.75	21	54	0.406	0.389	-0.017
1.00	22	76	0.571	0.482	-0.090
1.25	4	80	0.602	0.560	-0.041
1.50	14	94	0.707	0.627	-0.080
1.75	1	95	0.714	0.684	-0.031
2.00	15	110	0.827	0.732	-0.095
2.25	1	111	0.835	0.772	-0.062
2.50	4	115	0.865	0.807	-0.058
2.75	1	116	0.872	0.836	-0.036
3.00	5	121	0.910	0.861	-0.049
3.25	0	121	0.910	0.882	-0.028
3.50	1	122	0.917	0.900	-0.017
3.75	1	123	0.925	0.915	-0.010
4.00	4	127	0.955	0.928	-0.027
4.25	0	127	0.955	0.939	-0.016
4.50	1	128	0.962	0.948	-0.014
4.75	1	129	0.970	0.956	-0.014
5.00	1	130	0.977	0.963	-0.015
5.25	0	130	0.977	0.968	-0.009
5.50	0	130	0.977	0.973	-0.004
5.75	0	130	0.977	0.977	0.000
6.00	1	131	0.985	0.981	-0.004
6.25	0	131	0.985	0.984	-0.001
6.50	1	132	0.992	0.986	-0.006
6.75	0	132	0.992	0.988	-0.004
7.00	0	132	0.992	0.990	-0.003
7.25	0	132	0.992	0.991	-0.001
7.50	0	132	0.992	0.993	0.000
7.75	0	132	0.992	0.994	0.001
8.00	0	132	0.992	0.995	0.002
8.25	0	132	0.992	0.996	0.003
8.50	0	132	0.992	0.996	0.004
8.75	1	133	1.000	0.997	-0.003

n = 35 Total number of delays =133. Total delay duration =202.25 hrs

X = 202.25/133 = 1.521 hrs/delay

DISCUSSION

Small delays

t_test for delay frequency between treatments mean

There is no evidence that the mean delay/cycle in light treatment is significantly different from that of heavy treatment (p-value for t-test = 0.1855). There is no evidence that the mean delay/cycle in light treatment is significantly different from that of light with opening treatment (p-value = 0.259). There is no evidence that the mean delay/cycle in heavy treatment is significantly different from that of light with opening treatment (p-value = 0.234)

t_test for delay duration between treatments mean

There is no evidence that the mean min/delay in light treatment is significantly different from that of heavy treatment (p-value for t-test = 0.1797). There is no evidence that the mean min/delay in light treatment is significantly different from that of light with opening treatment (p-value = 0.0986). The mean min/delay in heavy treatment is significantly different from light with opening treatment (p-value = 0.0175).

As there is no significant difference of delay frequency and delay duration between the treatments, therefore, delay data are combined and the mean delay/cycle and mean minute/delay are 0.601 (std. dev. = 0.153) and 0.904 (std. dev. = 0.499) respectively.

Chi-square test for frequency distributions between treatments

The small Chi-square (χ^2) value (5.145) compared to critical value of χ^2 at $\alpha = 0.05$ (9.488) reveals that there is no significant difference of delay frequency between the treatments. So the three treatments can be combined for analysis.

Chi-square test for duration distributions between treatments

The large χ^2 value (31.313) compared to critical value of χ^2 at $\alpha = 0.05$ (15.507) shows a significant difference of delay duration between the treatments. The greater part of this χ^2 value is due to the bigger differences between theoretical and observed number of turns in heavy and light with gap thins corresponding to the duration group 'other'. The observed number in heavy treatment is under reporting and in light with opening treatment over reporting than that of the expected theoretical number of turns in those two treatments. For duration up to 80 cmin the number of turns for the three treatments appear close to their respective expected numbers.

Chi-square test for delay category distribution

The Chi-square value (59.57) is greater than the critical value of Chi-square at $\alpha = 0.05$ (12.592), which shows a significant difference between the treatments. Likewise, the major amount of this Chi-square value is contributed mainly due to under reporting in heavy thin and over reporting in light with gap thin compared to corresponding expected values for code ‘other’. Except for this code, the values in the cells are close to the theoretical expected values.

Considering these under reporting and over reporting cases as exceptions, the three treatments are similar with respect to frequency, duration and code-wise distribution. Hence the three treatments can be combined.

K-S test for small delay frequency fit with Poisson

Poisson distribution was tried individually for frequencies for each treatment. The differences obtained between Poisson observed cumulative and theoretical cumulative frequencies are much smaller than the critical value for the differences to be fit with the expected Poisson curve. This means the observed curve shows a good fit with the theoretical curve. In other words, the delay frequencies in each of the treatments are Poisson.

The data was then combined to try the fit with the Poisson curve. The differences obtained between Poisson observed cumulative and theoretical cumulative frequencies are much smaller than the critical value of differences to be fit with the expected Poisson curve. This means the observed curve of observed data shows a good fit with the theoretical curve. That is, the distribution of delay frequencies is Poisson.

K-S test for small delay duration fit with exponential

For the combined delay data the difference obtained between observed cumulative and theoretical cumulative number of delays for each duration interval are much smaller than the critical value of difference to be fit with the expected K-S curve. That is, the observed curve shows a good fit with the theoretical exponential curve.

Large delays

Chi-square test for large delay frequency

The high Chi-square value (23.45) shows that the observed curve does not fit with the Poisson theoretical curve. We cannot fully rely on the result of this χ^2 test until the result is confirmed with the K-S test.

K-S test for large delay frequency

An attempt was made to fit the combined data to the Poisson curve. The differences obtained between Poisson observed cumulative and theoretical cumulative frequencies are much smaller than critical value of difference (0.24) to be fit with the expected Poisson curve. This means the observed curve shows a good fit with the theoretical curve. In other words, the distribution of delay frequencies is Poisson. Although the observed cumulative frequencies are within the range of the critical values to be fit with Poisson curve, the actual shape of the curve deviates slightly from theoretical Poisson curve.

K-S test for large delay duration fit with Exponential

For the combined delay data the difference obtained between observed cumulative and theoretical cumulative number of delays for each duration interval are much smaller than the critical value of difference to be fit with the expected K-S curve. That is, observed curve shows a good fit with the theoretical exponential curve.

SUMMARY AND CONCLUSION

A comprehensive delay analysis is performed in this paper. Small and large delay data respectively from detailed time study and shift level study of the walkthin skyline yarding operations of the Willamette Young Stand Project were used. The three thinning treatments involved are light, heavy, and light with opening. The study project was located in the Central Western Cascades of Oregon. Small delays (less than 10 minutes) and large delays (10 minutes and more) were obtained from detailed time study and shift level study respectively. Delays were categorized with code. Delay data were sorted on the basis of frequency (delay/cycle) and duration (minutes/delay).

The t-test at the 95% confidence level was done to see the differences between treatments for frequency and duration. Chi-square test with contingency table was done to check the observed curve with theoretical distribution for small delay frequency, duration, and code-wise distribution and also for large delay frequency and duration. Poisson and exponential distributions were checked for delay frequency and delay duration respectively. K-S tests were performed for confirming these distributions.

Small delays

There is no evidence that mean delays/cycle and mean minutes/delay are different between the treatments. The treatments are combined and mean delays/cycle is 0.601 and mean minutes/delay is 0.904.

From a Chi-square test there is no significant difference of delay frequency distribution between the treatments. So the three treatments data for delays/cycle can be combined

The Chi-square test of delay duration shows a significant difference between treatments. The greater part of this Chi-square value comes from duration group 'other' for heavy and light with opening treatments. Aside from this duration group the theoretical values are close to observed values. The same result is obtained for the Chi-square test of code-wise distribution. For an unidentified reason, heavy treatment is under reporting and light with opening treatment is over reporting in the cells of the contingency table.

On the other hand K-S test result contradicts the Chi-squared results and shows that observed curve for delay frequency fits with the theoretical Poisson curve.

It is concluded from K-S test that the observed curve for delay duration fits the theoretical Exponential curve.

Large delays

The Chi-square test shows that the observed frequency curve does not fit with the Poisson theoretical curve. But the K-S test on frequency contradicted this result and shows a good fit of observed curve with theoretical curve. That is, the distribution of delay frequency is Poisson. The K-S test on delay duration also shows good fit of the observed curve with the theoretical K-S curve.

The t-test, Chi-squared, and K-S tests appear to be good tools for statistical testing of delays. Treatment differences in the mean value of both delay frequency (delays/cycle) and duration (min/delay) can be done with the t-test. In general we found that treatment differences did not exist. The Chi-squared test can be used to test if there are treatment differences in the distribution of frequency, duration, and code type. We found treatment differences in some of these categories. The K-S test was effective in determining if the curves fit the theoretical distributions, Poisson for frequency and exponential for duration. In general the frequency was Poisson and the duration was exponential. This was true especially for the large delays.

Chapter 4

SIMULATION OF TIMBER HARVESTING OPERATION DELAYS

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INTRODUCTION

When studying harvesting productivity, delays constitute a considerable portion of the total time. Proper measurement and estimation of delays is an important part of evaluating system performance. In most operations, delays makeup at least 25% of the total time. This is typically equally divided between small (under 10 minutes) and large (equal and over 10 minutes) delays. This standard definition has been used by North American work study teams. Shift level studies usually record large delays while detailed time studies concentrate on the small delays. An analyst is tempted to find significance in the pattern of the percentage estimate of delays over time. Simulation however can demonstrate that this apparent pattern may be only random variation.

Simulation will be used to demonstrate the confidence interval of delays that would be observed for various lengths of studies. In this chapter delays are randomly generated by using the mean and standard deviation of actual data. Then the cumulative average percent delay is calculated as the sample size increases.

The simulation of delays has the advantage of being able to replicate under identical conditions. These replications will help demonstrate the meaning of the confidence interval around the estimated mean percentage delay. In this chapter, we will investigate the study length needed to accurately predict delays. The number of cycles (for small delays) and number of days (for large delays) are the respective study lengths. The confidence interval can be used to determine the length of study that is necessary to achieve a specific degree of accuracy in the estimate of the mean percentage. The mean delay percentages will be determined by combining delay frequency and delay duration.

Literature review

Thompson (1988) described periodic (scheduled maintenance, breaks, etc.) and random occurrences (delay, break down, etc.) of unproductive time in his standard format of reporting machine performance. He mentioned that the amount of time required to perform each element will vary from cycle to cycle as a function of many different factors. If these individual elements are measured enough times, a reliable average time can be calculated if conditions do not change.

Riggs, et al. (1994) developed formula to calculate composite variances when mean and standard deviation of two variables are known. This formula for variance multiplication will be used in this chapter.

As the time between delay occurrences is exponentially distributed, the spread sheet formula reported by Pritsker (1986) will be used for generating exponential variates.

The previous length of study design is on the basis of delay free turn time using a regression model. Olsen et al., (1998) demonstrated the procedure of study length determination using detailed and shift level delay free regression equations. No other study has yet been done for determining study length or sample size on the basis of delay information.

Delay distributions

One of the necessary simulation inputs is the distribution of the delays. The time between occurrences of the delays is exponentially distributed (this is equivalent to saying the delays per day are Poisson) (Hillier, et al. 1995). Likewise the duration of the delays followed the exponential distribution as demonstrated in chapter 3. This suggests that how often a delay will occur and how long the delay will last are purely independent random events.

Hypothesis

Simulation of delays can be used to determine study length.

Objective of the study

To determine study length based on large and small delay data

METHODS AND PROCEDURE

The skyline yarding time study data from Walkthin site of Willamette National Forests of USFS were used in this paper. The site was located in Central Western Oregon of USA. The small and large delay data were obtained from detailed time study and shift level study respectively.

Small delays

Because small delays occur much more frequently, about once per cycle, we should be able to make better estimates. We can observe several hundred cycles during a study of 4 days. Our ability to accurately predict the percentage of the time taken by the small delays is enhanced as time increases. A relatively small confidence interval will result.

A small delay occurred on the average about once every 8.2 min (0.601 delays per 4.93 min cycle). The duration averaged 0.904 min per delay (Figure 4.1). By dividing 0.904 by 8.2 we will obtain 11.02% covered by delay. The variance of this percentage is calculated via the composite of the frequency and duration variation. The time between delays is exponentially distributed whenever the delay frequency (delay/cycle) is Poisson (Hillier, et al., 1995).

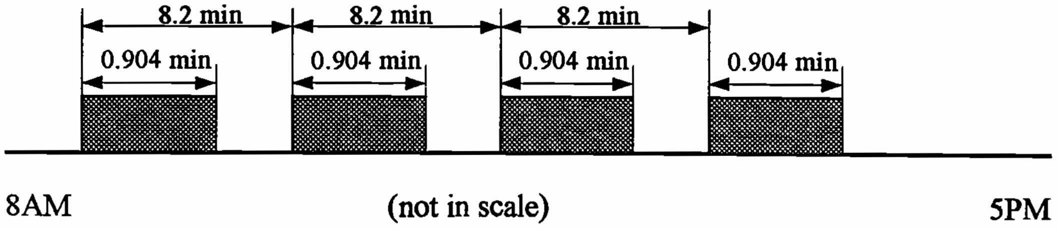

Figure 4.1. Average interval and duration of small delay occurrence

The delay frequency is the number of small delays per cycle for detailed time study data. This is because, the cycle is considered the unit time for delay analysis for small delays. Whereas, delay duration is the duration in minutes. To simplify assume that frequency and duration are two completely independent random variables. The occurrences of one and/or magnitude of one does not depend on the other.

The equation for the variance of the product of two independent random variables can be obtained through a series of operations. The expression stated in terms of the mean μ and varianceσ^2 of the component distributions is

$$\sigma_P^2 = \sigma_{AB}^2 = \mu_A^2\sigma_B^2 + \mu_B^2\sigma_A^2 + \sigma_B^2\sigma_A^2$$

The variance of the Poisson is equal to the mean:

$$P(x) = \beta^x e^{-\beta} / x! \qquad \text{x} = 0,\ 1,\ 2,\ \ldots\ldots$$

$$E(x) = \beta \qquad \text{var}(x) = \beta \qquad \hat{\beta} = 0.601$$

The variance of the Exponential is the square of the mean:

$$f(x) = \beta e^{-\beta x} \qquad x \geq 0$$

$$E(x) = 1/\beta \qquad \text{var}(x) = 1/\beta^2 \qquad 1/\hat{\beta} = 0.904$$

Substituting in the two mean values of 0.601 and 0.904 gives a composite variance:

$$\sigma^2 = 0.904^2 * 0.601 + 0.601^2 * 0.904^2 + 0.904^2 * 0.601 = 1.277$$

$$\sigma = \sqrt{1.277} = 1.13\,\text{min}/\mathit{cycle}\,; \quad \sigma_P = 1.13/4.93 = 0.2293 = 22.93\%$$

The square root of this variance leads us to a standard error term based on the sample size (number of cycles).

$$\sigma_{\overline{P}} = \sqrt{\frac{\sigma_P^2}{n}} = \frac{\sigma_P}{\sqrt{n}} = \frac{22.93\%}{\sqrt{n}} = \frac{0.2293}{\sqrt{n}}$$

The confidence limits form a band around the small delay percentage:

$$\overline{P} \pm Z\sigma \quad = P \pm 1.645\frac{\sigma}{\sqrt{n}} = 0.1102 \pm 1.645\frac{0.2293}{\sqrt{n}}$$

Z = 1.645 for 90% confidence level.

Large delays

A large delay occurred on the average about once every 11.6 hours (0.69 delays per 8 hour day). The duration averaged 1.31 hours per delay. By dividing 1.31 by 11.6 we will obtain 11.3%. The variance of this percentage is calculated via the composite of the frequency and duration variations.

The delay frequency is the number of large delays per day for shift level data. This is because a day is considered the unit time for delay analysis for large delays. Whereas, the delay duration is the duration in minute. Again assume that frequency and duration are two completely independent random variables, the occurrences of one and/or magnitude of one do not depend on the other.

The equation for the variance of the product of two independent random variables can also be obtained in the same manner as the small delays.

The variance of the Poisson is equal to the mean:

$$E(x) = \beta \qquad \mathrm{var}(x) = \beta \qquad \hat{\beta} = 0.69$$

The variance of the Exponential is the square of the mean:

$$E(x) = \frac{1}{\beta} \qquad \mathrm{var}(x) = \frac{1}{\beta^2} \qquad 1/\hat{\beta} = 1.31$$

Substituting in the two mean values of 0.69 and 1.31 gives a composite variance:

$$\sigma^2 = 1.31^2 * 0.69 + 0.69^2 * 1.31^2 + 1.31^2 * 0.69 = 3.1851$$

$$\sigma = \sqrt{3.1851} = 1.785 \quad \mathit{hours/day}$$

$$\sigma_P = 1.785/8 = 0.223 = 22.3\%$$

The square root of this variance leads us to a standard error term based on the sample size (number of days).

$$\sigma_{\overline{P}} = \sqrt{\frac{\sigma_P^2}{n}} = \frac{\sigma_P}{\sqrt{n}} = \frac{22.3\%}{\sqrt{n}} = \frac{0.223}{\sqrt{n}}$$

The confidence limits form a band around the large delay percentage:

$$\overline{P} \pm Z\sigma \;= P \pm 1.645\frac{\sigma}{\sqrt{n}} = 0.113 \pm 1.645\frac{0.223}{\sqrt{n}}$$

Z = 1.645 for 90% confidence level

ANALYSIS AND RESULTS

Simulation theory on small delays

It is possible to generate an exponential variate by using the following function (Pritsker, 1986):

$$X = -U*ALOG(RAND)$$

Where: X = the exponentially distributed random variate
U = the mean of the exponential distribution
$ALOG$ = the natural logarithm
$RAND$ = a uniform random variable with range 0.0 to 1.0

A spread sheet was used to generate 200 delays. First the time between each delays was generated using the spreadsheet formula for the exponential function:

Minutes *until next delay = -8.20*@LN(@RAND)*

Then the duration of the delays was generated by using spreadsheet formula:

Duration = -0.904@LN(@RAND)*

A cumulative average percentage is calculated by summing the duration and dividing by the minutes between delays.

$$\text{Cumulative average percentage} = \frac{\sum \text{duration}}{\sum \text{time between delay occurrences}} * 100$$

This simulates the percentage of time for delays. The cumulative average shows how this estimate of percentage improves with longer studies.

Graph of replications

The simulation was replicated for ten periods of 334 cycles. The cumulative averages were then plotted along with the confidence band. The resulting plots (Figure 4.2) show how the predicted mean percentage of delays can fluctuate. The oscillation of the curve dampens as the length of the study increases. Over time all ten of the curves begin to approach the correct value of 11.02%. With a study length of 334 cycles, however, the 90% confidence interval is still

$$1.645 * \frac{0.2293}{\sqrt{334}} = 0.0206 = \pm 2.06\%$$

We have full control on this standard error term because we can lengthen or shorten the detail time study data collection period.

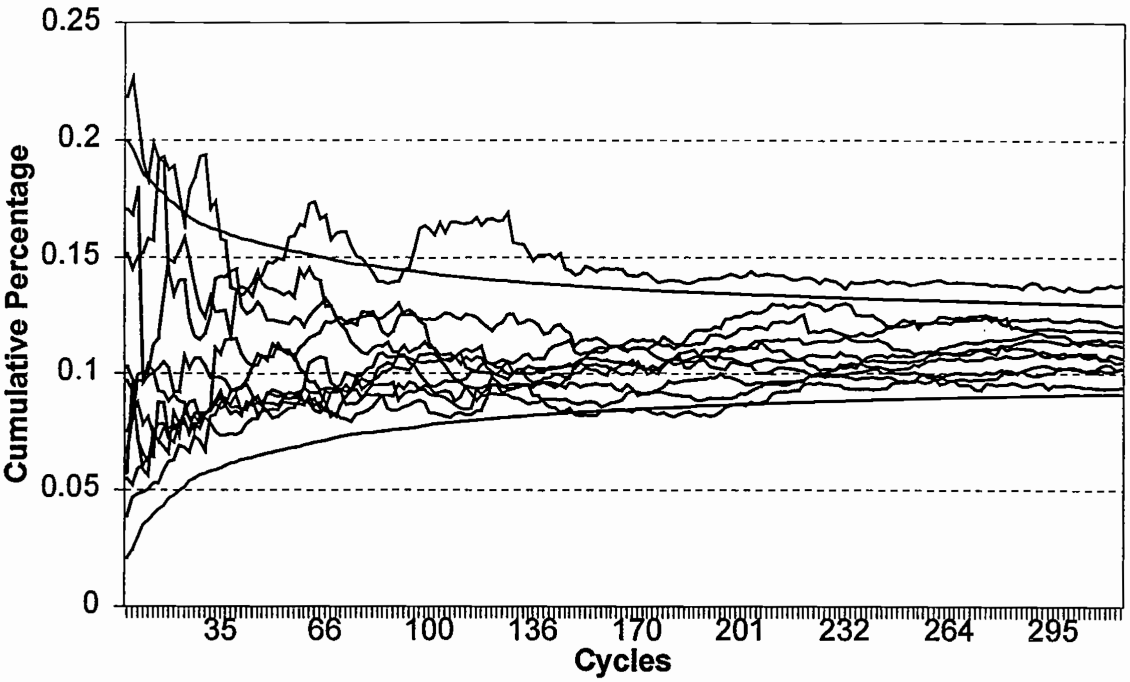

Figure 4.2. Walkthin skyline yarding small delays simulation at 90% control limits

Simulation theory on large delays

A spread sheet was used to generate 100 delays. First the time between each delays was generated using the spreadsheet formula:

Hours until next delay = -11.6@LN(@RAND)*

Then the duration of the delays was generated by using spreadsheet formula:

Duration = -1.31@LN(@RAND)*

A cumulative average percentage is calculated by summing the duration and dividing by the hours between delays.

$$\textit{Cumulative average percentage} = \frac{\sum \textit{duration}}{\sum \textit{time between delay occurrences}} * 100$$

Graph of replications

The simulation was replicated for ten periods of 140 days. The cumulative averages were then plotted along with the confidence band. The resulting plots (Figure 4.3) show how the predicted mean percentage of delays can fluctuate. The oscillation of the curve dampens as the length of the study increases. Over time all ten of the curves begin to approach the correct value of 11.3%. With a study length of 140 days, however, the 90% confidence interval is still

$$1.645 * \frac{0.2231}{\sqrt{140}} = 0.0368 = \pm 3.68\%$$

The standard error term here is much bigger than that in small delay. The standard error term can be decreased by increasing study length (n).

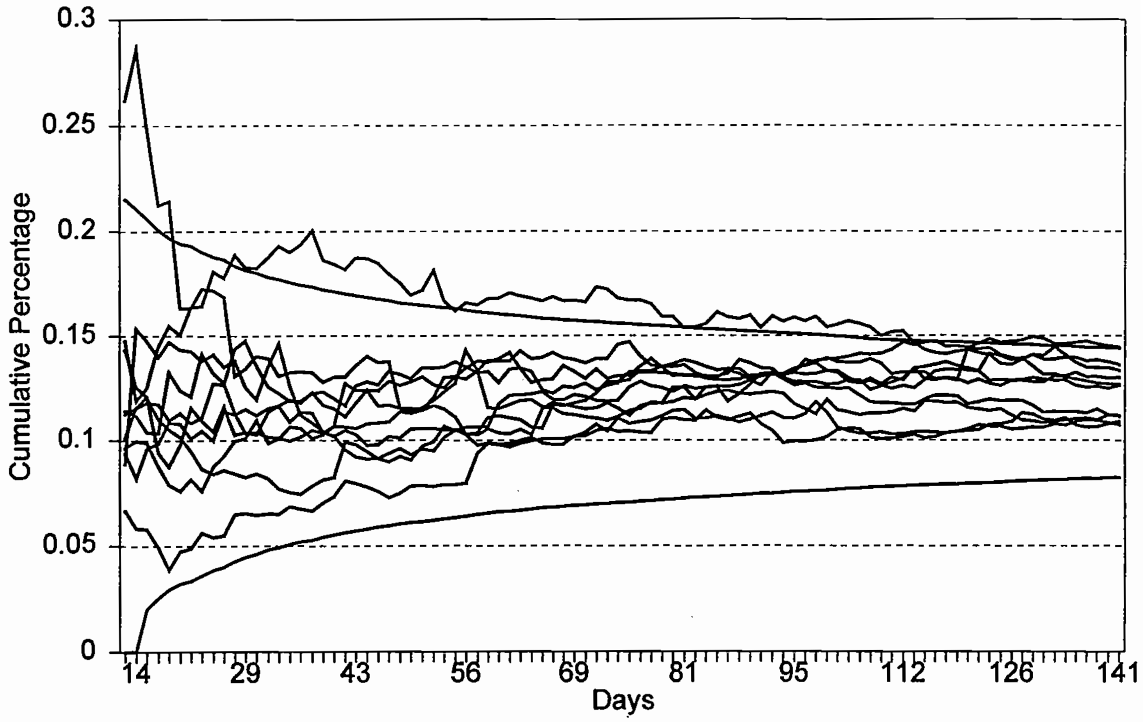

Figure 4.3. Walkthin skyline yarding large delays simulation at 90% control limits

DISCUSSION

Small delays

As a check on our confidence interval we will calculate a cruder estimate using the binomial distribution as it applies to proportions. Using binomial theory the confidence interval is estimated at:

$$\sigma_{\bar{p}} = \sqrt{\frac{p(1-p)}{n}} = \sqrt{\frac{(0.1102)(0.889)}{n}} = \frac{0.313}{\sqrt{n}}$$

This is overly pessimistic in light of the actual curves observed and the composite interval calculated earlier. The standard error term, $0.313/\sqrt{n}$, is bigger than that of present analysis, $0.2293/\sqrt{n}$.

It would be reasonable to design a study period for a production study to be 334 cycle (about four days of detailed time study)(Figure 4.2). We can see from the graph that at this point the confidence interval is ±2%. And there is a 10% chance that the true average percentage will be outside of the confidence band. It is visualized that one out of ten (10%) random curves points tends to fall outside the bend.

Large delays

As a check on our confidence interval we will calculate a cruder estimate using the binomial distribution as it applies to proportions. Using binomial theory the confidence interval is estimated at:

$$\sigma_{\bar{p}} = \sqrt{\frac{p(1-p)}{n}} = \sqrt{\frac{(0.113)(0.887)}{n}} = \frac{0.317}{\sqrt{n}}$$

This is overly pessimistic in light of the actual curves observed and the composite interval calculated earlier. The standard error term, $0.317/\sqrt{n}$, is bigger than that of present analysis, $0.223/\sqrt{n}$.

It would be unusual for a production study to be longer than 36 days. We can see from the graph that at this point the confidence interval is ±6%. And still there is a 10%

chance that the true average percentage will be outside of the confidence band. It is visualized that as expected one out of ten random curves points falls outside the band.

It is unlikely that we could collect sufficient data to accurately estimate the percentage of large delays. When comparing two operations it is best to record the large delays and then remove them from the data. The productivity could then be compared on a delay free basis.

On the other hand, it is very easy to collect sufficient data to accurately estimate the percentage of small delays.

SUMMARY AND CONCLUSION

The skyline yarding time study data from Walkthin site of Willamette National Forests of USFS were used in this paper. The site was located in Central Western Oregon of USA. The small and large delay data were obtained from detailed time study and shift level study respectively.

Proper measurement and accurate estimation of delays is an important part of evaluating system performance. Delays generally cover about 25% of scheduled time. It consists of two parts small delays and large delays.

The time between delays and duration of delays were randomly generated by using means and standard deviations of both small and large delays. Then the cumulative average of delay was calculated. The number of cycles for small delays and number of days for large delays needed were investigated to accurately predict delays. The confidence interval was used to determine the length of study necessary to achieve a specific degree of accuracy in the mean delay percentage estimation.

The small delays occurred very frequently, on the average once every 8.2 min with a duration of 0.904 min. per delay. The resulting mean delay percentage was 11.02 and standard error of 0.2293/√(number of cycles).

The large delays occurred on the average once every 11.6 hours with a duration of 1.31 hours per delay. The mean delay percentage obtained was 11.3 and standard error of 0.223/√(number of days).

The simulation of both small and large delays were replicated 10 times. For small delays 11% mean delays was obtained at study length of 334 cycles and with 90% confidence interval of ±2%. For large delays 11.3% mean delays was obtained at a study length of 140 days and with 90% confidence interval of ±3.68%. To obtained 36 days of real data collection period the 90% confidence interval will be ±6%.

The reason for smaller confidence interval in small delays than large delays is the accuracy of detailed time study data is better than the shift level data. It is very easy to collect sufficient data to accurately estimate the percentage of small delays within an acceptable standard error.

Chapter 5

COMPARISON OF SHIFT LEVEL AND DETAILED TIME STUDIES

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INTRODUCTION

The two data collection techniques commonly used in harvesting operations are detailed time study and shift level study. Detailed time study is intensive, accurate and short term data collection method. In this method each individual work element is measured for each operation cycle. On the other hand, shift level study is long term and a general method of observing daily averages of production data. These two methods are different with respect to accuracy, cost and nature of the information collected. This chapter is focused mainly on the comparison of shift and detailed time studies to see the strengths and weaknesses of one versus the other. Although the activity sampling data were also collected in the same project, it will not be compared directly with the shift and detailed type of studies. Brief analysis of activity sampling data is reported in Appendix H for demonstration purpose

Description of shift level study

Shift level data records daily summaries of number of turns, piece count, hours worked, crew size, and major delays (over 10 minutes). A sample shift level skyline yarding recording form is shown in Appendix Figure G.1. These studies last for weeks or sometimes months (Olsen et al, 1998). Generally one person is chosen from the crew to be responsible for filling out the forms daily. One person from the crew also records the scale ticket information on the log trucks. Road and landing change information is recorded to the nearest 10 minutes (Kellogg et al, 1997). This study is conducted over the period of harvesting.

Description of detailed time study

The detailed time studies are recorded by handheld computers. The data are then down loaded to personal computer spreadsheets for screening and data management. Generally one or two researchers are engaged for collecting all of the data. The study usually lasts one week or less. Turn times are recorded along with associated variables like yarding distance, lateral distance, carriage height, etc. Both small delays (less than 10 minutes) and large delays (over 10 minutes) are recorded.

In this chapter, these two techniques were compared as they apply to determining productivity of commercial thinning operations and relative efficiency, accuracy, and usefulness in operations. Only three treatments of the skyline yarding operation were used in the walkthin site as an example for demonstrating a comparative analysis.

Literature review

No study was found which is similar to the comparison technique adopted in this chapter. A study by Olsen et al. (1983) used (1) shift level summaries, and (2) stopwatch techniques for evaluating logging production. They performed paired t-test for comparing the two methods. The results showed that overall production levels were 2%

less with shift level data than with stopwatch data. This difference was not significant at a 95% confidence level. The study also showed that one of the shortcomings of shift level data is it does not diagnose or explain any of the factors contributing to the measurement of productivity. Thus, the production average is valid only for the site's specific logging conditions. Other than this study none compared shift level studies with the detailed time study.

Lussier (1961) used a technique to compare ratio of delays for two different timing methods: continuous timing, and work sampling. He used the following formula for testing significance of difference by using the t statistic:

$$t = \frac{\tilde{p} - p}{\sqrt{\frac{p(1-p)}{n}}}$$

Where $\tilde{p}$ = ratio delay obtained from work sampling
p = ratio delay obtained from continuous timing.

He found no significant difference between the two methods (t=0.91).

The following studies measure productivity in harvesting.

FERIC conducted a study on three cable yarding systems harvesting old growth forest in west coast of Vancouver Island in British Columbia (Forrest, 1995). Both shift level and continuous timing measurements were performed. The objective of the study was the estimation of productivity and costs. The three systems were, choker yarding using a swing yarder with a fixed backspar, grapple yarding using a swing yarder with a mobile backspar, and choker yarding using a mobile steel tower in running skyline with a mobile backspar. The study was performed to evaluate production and cost, quality of merchantable logs recovered, site disturbance, and fiber left on the site after harvest.

A study on tree-length wheeled skidding operation in northwestern Ontario was done by Cottell,et al. (1971). Three levels of study were conducted simultaneously on the operation: the shift level, in which the measurement of specified factors were made once per shift; the turn level, in which measurements were made once per turn; and the turn-element level, in which each element of every turn was measured. The analysis of this study showed the significant differences in the estimates of average production (cunits/hr) among the three levels of study. The authors of this paper defined shift level and other measurements differently than ours.

A partial cutting trial was conducted in a second growth douglas-fir stand on Quadra Island, British Columbia (Bennett, 1993). A 1991 John Deere 450G crawler tractor was used as primary skidding machine. A 1979 John Deere 540 rubber-tired cable skidder was used intermittently to augment log forwarding on the designated skid roads. Productivity and costs were evaluated by collecting shift-level and detailed timing information. The shift-level time study was conducted using DSR servis recorders mounted in the cabs of the crawler tractor and skidder to produce automatic charts with daily shift reports describing falling, skidding activities, and log production. The detailed timing of skidding-cycle elements over ten shifts were done by hand-held computer. This study was conducted for the comparative productivity measurement between two different machines.

All of the above studies were conducted for computing production and costs. None of the studies were done for comparing strengths and weaknesses between shift level and detailed time studies.

Justification of the study

When designing a production study it may be desirable to use either detailed time study, shift level study or both. A detailed time study gives more information than shift level study, but the information offered by the two techniques is different in nature. Detailed time study is more expensive than shift studies. That means one method is complimentary to the other. So analysis of the two is of utmost importance before deciding how best to collect data, which method(s) and how long each is to be used, to fulfill the harvesting objectives and to make the study cost effective.

Hypothesis

Results of detailed time study and shift level study are not same.

Objectives of the study

For a harvesting production study:

1. Compare the results from collecting data with a detailed time study versus shift level study
2. determine an appropriate study length using each technique

METHODS AND PROCEDURE

In this study three thinning treatments of skyline cable yarding operations of Walkthin site were selected to compare detailed time study and shift level study. The treatments were three levels of thinning intensity. Multiple linear regression models were built combining three treatments using shift level and detailed time study data. Indicator variables (Table 5.1) were used in combining the treatments in the model. Forward stepwise multiple regression in Statgraphic Plus was used to develop a model for predicting delay-free mean cycle per productive machine hour (pmh) based on significant ($P \leq 0.05$) independent variables. Multicolinearity was checked before selecting independent variables to include in the model. The weighted average of independent variables values among the all three treatments were calculated to predict the mean cycle/pmh. The weighted standard errors were also calculated for both types of study.

Table 5.1. Layout of indicator variables for treatments

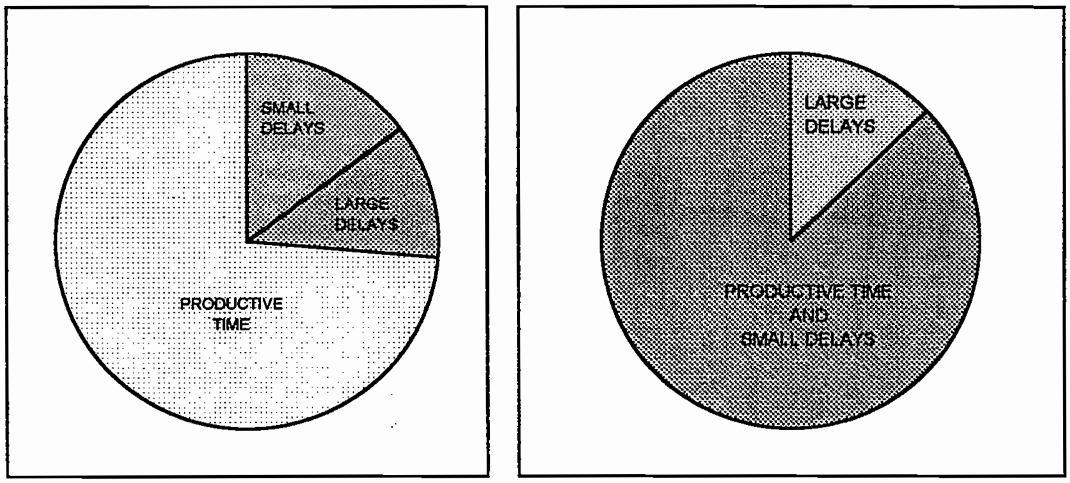
Treatment	Heavy	Light with Opening
Light [1]	0	0
Heavy	1	0
Light with Opening	0	1

[1] Light thin is used as base for comparing it with other two treatments

The shift level predicted mean cycles per hour (pmh) has the large delay (over 10 minutes) removed. Figure 5.1 demonstrates productive time and delays in two methods. Small delays are confounded with the turn time because small delays were not timed in shift level. There is no reasonable way to calculate the small delays and to remove them from the shift data. So the average small delays calculated from the detailed time study was used to adjust shift level delay free predicted cycle per hour.

The plot of residual vs. predicted cycles/pmh for both models were studied to see if there are any outliers or if a pattern exists in the residuals.

The confidence band width of predicted mean cycles per pmh over increasing lengths of study (days) were drawn for both shift level study and detailed time study. In



a. Detailed time study b. Shift level study

Figure 5.1. Productive time and delays in two study methods

shift level study one row of observation was obtained for each day. So, each day is the unit of observation in shift level studies. The standard deviation (standard error of Y estimate) directly obtained from shift level regression equation is the daily standard deviation. On the other hand, in detailed time study each cycle is one observation. For comparison purposes, it is necessary to convert the detailed per cycle standard error to daily standard deviation. The daily standard deviation for the detailed data was derived from the standard deviation per cycle (the standard error of Y estimate obtained from detailed regression model) by weighting it with the average number of turns per day.

ANALYSIS AND RESULTS

Shift level study

The multiple linear regression equation developed from the shift level study to predict delay free mean cycles per pmh is

Coefficient (Variable)	P-value	Average value	Range
Mean Cycle/pmh = 5.076	0.0000	Constant (cycle/pmh)	
- 0.373 (DAYS)	0.0007	1.833 (# of day on corridor)	(1-5)
+ 1.631 (HEAVY)	0.0000	0,1 (indicator variable)	(0-1)
+ 0.785 (LGHT_OPEN)	0.0010	0,1 (indicator variable)	(0-1)
+ 0.023 (LOGS)	0.0000	140.22 (number/day)	(8-262)
+ 0.006 (TOPS)	0.0003	190.25 (number/day)	(48-538)

($R^2_{adjusted}$ = 59.53%; Standard error of Y estimate = 1.335 (standard deviation of residual); Sample size = 198 work days).

The variable FIBER is not significant at 95% level ($P \geq 0.05$) in the model. The small number of fiber pieces per cycle may be responsible for this. No long term TREND effect was found. Standard error for the mean response of the light treatment sample is calculated as follows:

$$\text{standard error} = \text{standard error per day} / \sqrt{\text{(number of days in sample)}}$$

$$= 1.335 / \sqrt{60} = 0.172$$

Small delays obtained from detailed time study is 13% of total cycle time. So, predicted shift level cycle per hour is adjusted with this delay percent to make it comparable with predicted detailed time study cycle per hour.

Detailed time study

The multiple regression equation developed from the detailed time study to predict delay (all delay) free mean cycles per pmh is

Coefficient (Variable)	P-value	Average value	Range
Mean Cycle/pmh = 15.271	0.0000	Constant (cycle/pmh)	
- 0.006 (YDIST)	0.0000	570.28 (feet)	(40-1200)
- 0.023 (LDIST)	0.0000	20.52 (feet)	(0-90)
- 0.009 (CARR_HGT)	0.0000	51.19 (feet)	(5-162)
+ 1.008 (PRESET)	0.0000	0.18 (indicator variable)	(0-1)

- 0.203 (LOGS)	0.0000	1.68 (number/turn)	(0-6)
- 0.306 (TOPS)	0.0000	1.84 (number/turn)	(0-8)
- 0.174 (FIBERS)	0.0030	1.21 (number/turn)	(0-8)
+ 1.830 (HEAVY)	0.0000	0,1 (indicator variable)	(0-1)
+ 1.023 (LGT_OPEN)	0.0000	0,1 (indicator variable)	(0-1)

($R^2_{adjusted}$ = 47.67%; Standard error of Y estimate = 1.76 (standard deviation of residual); Sample size = 937 yarding cycles).

Standard error for the whole sample is calculated as follows

$$\text{standard error} = \text{standard error per cycle}/\sqrt{(\text{number of cycle in sample})}$$
$$= 1.76 / \sqrt{285}$$
$$= 0.104$$

The predicted mean cycle/pmh and its standard error for both shift and detailed time study are shown in Table 5.2.

Table 5.2 Comparison of predicted cycles/pmh of two studies using t-test

Treatment	Shift			Detailed			P-value
	Predicted Cycles/ Pmh[1]	Std. Error	Sample Size (days)	Predicted cycles/ Pmh	Std. Error	Sample Size (cycles)	for comparing differences between shift and detailed
Light	10.07	0.172	60	9.98	0.104	285	0.3276
Heavy	11.97	0.183	53	11.81	0.101	301	0.2224
Light w/ Opening	10.96	0.145	85	11.00	0.094	351	0.4087
Average	10.96	0.095		10.95	0.057		
Total			198			937	

[1] Adjusted with small delay percent obtained from detailed time study

Confidence interval

Figure 5.2 shows the confidence intervals of predicted mean cycle per pmh over length of study (days) as x-axis for both shift level study and detailed time study.

Shift level study

Daily standard deviation = 1.335 cycles/pmh

$$95\%\ C.I.\ = mean \pm 1.96\ \frac{1.335\ \text{cycles/}pmh}{\sqrt{n}}$$

where: *mean* =10.96 cycles/pmh

n = number of days

Detailed time study

Standard deviation per cycle = 1.76 cycles/pmh

$$95\%\ C.I.\ = mean \pm 1.96\ \frac{S_{daily}}{\sqrt{n}}$$

where:

$$S_{daily} = \frac{S_{percycle}}{\sqrt{number\ of\ \text{cycles/}day}} = \frac{1.76\ cycles/pmh}{\sqrt{73.54\text{cycles/}day}} = 0.235\ \text{cycles/}pmh$$

S_{daily} = daily standard deviation

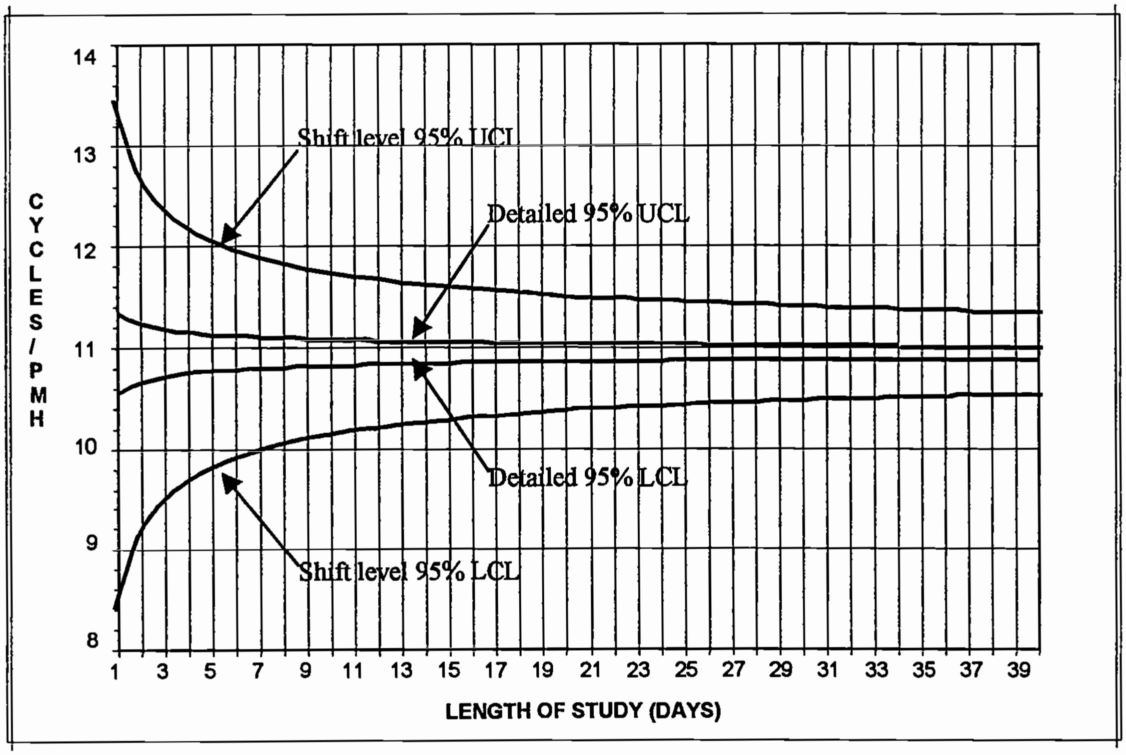
$mean$ = 10.95 cycles/pmh

$S_{per\ cycle}$ = standard deviation per cycle

n = number of cycles.

The 95% confidence interval formulae for both shift level study and detailed time study shown in this section were used for developing the Figure 5.2. All terms of the formula are assumed to be constant except the number of days (n) and number of cycle (n) in shift and detailed respectively. The purpose of this assumption was for simplicity and for illustration . The average number of cycles per day (=73.54) of detailed time study was used to convert number of cycles into days. In this way confidence intervals of cycles per hour are plotted against number of days of study as shown in Figure 5.2.

Figure 5.2. Comparative confidence interval of cycles per hour for shift and detailed



DISCUSSION

Shift level study

The shift level multiple regression model was developed on mean cycle per pmh. Results show that for each additional day on the same corridor the output is decreased by 0.373 cycles/pmh (P-value = 0.0007). This is because the yarding distance increases each day on the corridor resulting in fewer cycles per hour. For increase of one log and one top per day the mean cycles per pmh is increased by 0.023 and 0.006 respectively (p-values in both cases less than 0.01). Compared with light thin as a base, the mean cycle per pmh in heavy thin is 1.631 more and light with gap thin is 0.785 (p-values are 0.0000 and 0.001 respectively).

Detailed time study

The detailed time study multiple regression model was developed on mean cycle per pmh.

As yarding distance, lateral distance or carriage height increases, cycle time also increases which causes number of cycle per hour to decrease. For an increase of one foot of yarding distance, the mean cycle per pmh is decreased by 0.0006 (p-value = 0.0000). The same for the increase of one foot of lateral distance and carriage height the mean cycle per pmh is decreased by 0.023 (p-value = 0.0000) and 0.009 (p-value = 0.0000), respectively. Presetting reduces the cycle time hence mean cycle per pmh is increased by 1.008 (p-value = 0.0000). For increase of each additional piece of log, top and fiber the mean cycle per pmh is decreased by 0.203, 0.306, and 0.174 respectively (p-values are 0.0000, 0.0000 and 0.003 respectively). The mean cycle per pmh in the heavy thin treatment in 1.83 more and in light with gap thin treatment 1.023 more than that in light thin treatment (both p-values are 0.0000).

Comparison

Regression models

The significant variables common to shift and detailed are HEAVY, LIGHT with OPENING, LOGS, and TOPS. But these are different in units. The units of LOGS and TOPS are number/day in shift and number/turn in detailed. The interesting findings are that the coefficients of LOGS and TOPS are positive in shift and negative in detailed. Which means that with an increase of one log and one top the mean turn/pmh is increased by 0.023 and 0.006 respectively in shift and decreased by 0.203 and 0.306 respectively in detailed. The variable FIBERS is significant only in detailed. The variable DAYS (i.e. number of days on a corridor) is available in shift level study only. The detailed regression equation has four more significant variables than the shift, which were not measured in the shift level data collection. Based on the R^2 values, the detailed regression explained 47.7% of the variation compared to 59.5% in the shift regression.

The variables HEAVY and LIGHT_OPEN are significant in both regression models. In shift level heavy thin will produce 1.631 cycles/pmh and light with opening thin 0.785 cycles/pmh more than light thin. In detailed heavy and light with opening thin will produce 1.83 and 1.023 cycles/pmh respectively than light thin.

The difference of the predicted mean cycle/pmh between detailed and shift individually for each treatment are not statistically significant (Table 5.2). The standard error for shift level study is higher than that in detailed (Table 5.2). That is, the standard deviation of the residual of shift level model is wider than that of detailed time study model. This may be due to the accuracy in the recording of detailed data over the shift level.

Confidence intervals

The shift level 95% confidence interval of predicted mean cycle/pmh is 6.5 times wider for an equivalent number of days than that of detailed (Figure 5.2). This demonstrates the precision of detailed time study over shift level study. These also show how long a study would need to be conducted in order to reduce the confidence band width to acceptable level. For this study to attain width of ± 0.20 cycles/pmh a detailed time study would be run for 4 days (in this case 74 cycles/day) and a shift level could achieve this level only after 171 working days. It is also possible to estimate a confidence interval corresponding to a known number of days of study. For this study after 2 days of data collection the detailed time study will provide confidence band width of ± 0.28 cycles/pmh and in the case of shift level study the corresponding band width will be ±1.83 cycles/pmh.

The cycles per pmh calculated in Figure 5.2 for the two types of studies are different. This is because detailed pmh is completely delay free while the shift level has small delays confounded in it. If small delays could be removed from the shift pmh data then its confidence band would come closer.

If large delays had not been taken out then the confidence band of shift level cycle per pmh would be much wider because of the presence of the additional standard error term from large delays.

SUMMARY AND CONCLUSION

The thinning treatments of skyline cable yarding operations of Walkthin site were selected to compare detailed time study and shift level study. Multiple linear regression models were built using shift level and detailed time study data. The weighted average of independent variable values among the all three treatments were calculated to predict the mean cycles/pmh. The weighed standard errors were also calculated for both studies.

The confidence band width of predicted mean cycles per pmh over lengths of study (days) were drawn for both shift and detailed. In shift, each day is the unit observation while in detailed each cycle is one observation.

Shift level result shows that for each additional day on the corridor the production is decreased by 0.373 per cycles per pmh. In detailed for an increase of one foot of yarding distance, lateral distance, and carriage height the cycles per pmh is decreased by 0.006, 0.023, and 0.009 feet respectively. The significant variables common to shift and detailed are HEAVY, LIGHT with OPENING, LOGS, and TOPS. The variable shift level DAYS (number of days on corridor) is the equivalent of yarding distance in detailed time study. The detailed regression had five more significant variables which were not measured in shift level. The detailed regression explained 47.7% of the variation compared to 59.5% in the shift regression.

Standard error for shift level study is higher than that in detailed and hence the shift level 95% confidence interval of predicted cycles/pmh is 6.5 times wider than that of detailed. This demonstrates the relative precision of detailed time study compared to shift level study. These also show how long a study would need to be conducted in order to reduce the confidence band width to an acceptable level. Study shows that to attain an width of ± 0.20 cycles/pmh a detailed time study would be run for 4 days and a shift level could achieve this level only after 171 working days. It is also possible to estimate confidence interval corresponding to a known number of days of study. The estimated cycles per pmh for the two studies are different. Because detailed pmh is completely delay free while the shift includes small delays.

Chapter 6

CONCLUSIONS

Because the study was done over a several year period on 15 different scenarios, it allowed for a wide variety of comparisons to be made. Also, since the study collected data with several time study techniques concurrently, it was possible to compare the techniques.

COMPARISON OF HARVESTING ALTERNATIVES

Confidence interval based on cycle time, delays, and timber volume was developed to compare harvesting costs. Comparisons were made between treatments, sites, and logging systems.

Comparison of treatments

The treatment comparison has the best standardization of conditions for this study because it was on the same site with the same equipment and crew. Using the average values of regression variables and a common delay percentage, the comparison can be made of each treatment within a site. The Tapthin yarding and the Millthin yarding showed no difference in any of the treatments. The Walkthin yarding, Tapthin skidding, and Millthin skidding found a difference between the light thinning and the other treatment(s). In Flatthin forwarding the light with openings was different than the other two treatments. The 95% confidence interval was in the range of ± $2/m^3.

The general conclusion is that there is not a marked difference in extraction costs between treatments. The comparison is with the light thin treatment as the base. The heavy thin was more expensive in the tractor logging cases. The light with openings was more expensive in the forwarding case. In the other cases, a given treatment was higher on one site and lower on another controlled by volume per cycle.

Comparison of sites

The sites were compared with each other for a given treatment. There are many sources of variation between sites, primarily differences in the equipment and crew, the logging method, the delays, corridor and landing changes, and the treatment of the fiber material. Although the final stocking was held constant, the volume removed per acre could not be controlled and is different between sites. Only comparisons on the skyline yarding sites were possible.

No significant difference was found between the Walkthin yarding and the Tapthin yarding on light treatments nor on light with opening treatments. All three sites were different on the heavy thin treatment. This demonstrates the range of costs that could be expected for a given treatment.

When a sensitivity analysis is done based on yarding distance the comparisons are more evident.

On the tractor skidding sites the light and heavy were both significantly different between the two sites. The Tapthin site had consistently higher costs.

Comparison of logging systems

The skyline yarding costs are approximately double the tractor skidding costs. The skyline costs are more sensitive to yarding distance, again increasing at a higher rate than skidding as the distance increases.

A comparison between the tractor and the forwarder can only be inferred. The mechanized system forwarding was only done on the Flatthin site. In addition the felling costs must also be included since the forwarding only works in combination with a harvester which bunches the wood along the skid trails prior to forwarding.

The harvester cost is much higher than the manual felling which accompanies the skidder operation. So although the forwarder has a cheaper cost than the tractor skidding for all treatments and over most of the extraction distances range, adding in the harvester cost negates the cost advantage. The results of comparison of this total cost for the light and heavy treatments are inconsistent. The two systems do not have statistically significant differences that are consistent. Production affects the costs very much. The reason for higher tractor harvesting costs at heavy thin treatment than light is due to the significantly lower production at that treatment.

As shown in Figure 2.20 on page 56 the harvester cost changes nonlinearly with DBH. At about 25 cm (10 in.) DBH the harvesting costs is minimum.

Relative differences among treatments, sites, and systems

The most dramatic and consistent differences in the study were between the skyline yarding costs and the tractor skidding. Under all conditions the skyline was far more expensive. As yarding distance increased the gap between costs widens even more.

The mechanized system has costs similar to tractor skidding at the study average distances and DBH. When either distances or tree size increases the harvester/forwarder system becomes cheaper than felling/skidding system.

Differences between sites were clear for skidding. The costs for skyline yarding sites tended to not be significant different from each other when compared for the same treatment. This demonstrates that a range of costs can be expected based on site specific operating conditions.

The experimental design of the study gave the best standardization of conditions for comparing among treatments. In about 1/2 of the parings a cost difference was established between treatments. Surprisingly the light thin with openings tended to be more expensive than the base case of light thin.

In two of six of the parings the heavy thin was more expensive than the base case of light thin. In general the costs of heavy thin and light with openings were similar.

It appears that the cost of the thinning treatments need not be a major consideration when deciding on wildlife habitat manipulation. The most dramatic impact will be caused by the steepness of the slope dictating whether skyline yarding is required.

Importance of confidence intervals and sensitivity analysis

The confidence intervals allowed us to test if differences in costs were significant. These intervals were calculated from the unexplained variation in cycle times, cycle volumes, and delay percentages. This is often omitted in reports on production and costs. In general the confidence intervals showed that the differences in costs were not statistically significant.

Conclusions from this study are only valid within the range of conditions studied. Sensitivity analysis showed that extraction distance and piece size have a dramatic effect on the costs. When making comparisons these variables must be standardized.

DELAY ANALYSIS

The t-test, Chi-square test, and K-S tests were useful to test the difference between treatment means. The distributions of delay frequency and delay duration were tested with theoretical curves.

Small delays

There is no evidence that mean delay/cycle and mean minutes/delay are different between the treatments. The treatments are combined and mean delay/cycle is 0.601 and mean minutes/delay is 0.904.

A Chi-square test revealed that there is no significant difference of delay frequency distribution between the treatments. So the three treatment's data for delays/cycle can be combined

The Chi-square test of delay duration shows a significant difference between treatments. The greater part of this Chi-square value comes from duration group 'other' for heavy and light with opening treatments. Aside from this duration group the theoretical values are close to observed values. The same result is obtained for the Chi-square test of delay category distribution.

K-S test result shows that the observed curve for delay frequency fits the theoretical Poisson curve.

It is concluded from the K-S test that the observed curve for delay duration fits the theoretical exponential curve.

Large delays

The Chi-square test shows that the observed frequency curve does not fit with the Poisson theoretical curve. But the K-S test on frequency contradicted this result and shows an acceptable fit of the observed curve with the theoretical curve. That is, the distribution of delay frequency is Poisson. The K-S test on delay duration also shows a good fit of the observed curve with the theoretical K-S curve.

The t-test, Chi-squared, and K-S tests appear to be good tools for statistical testing of delays. Treatment differences in the mean value of both delay frequency (delays/cycle) and duration (min/delay) can be done with the t-test. In general we found that treatment differences did not exist. The Chi-squared test can be used to test if there are treatment differences in the distribution of frequency, duration, and delay category. We found treatment differences in some of these types. The K-S test was effective in determining if the curves fit the theoretical distributions, Poisson for frequency and exponential for duration. In general the frequency was Poisson and the duration was exponential. This was true especially for the large delays.

DELAY SIMULATION

Confidence intervals were used to demonstrate the effect of study length on small and large delay percentages. Simulation of percentage delay was replicated against length of study.

The small delays occurred frequently, on the average once every 8.2 min with a duration of 0.904 min. per delay. The resulting mean delay was 11.02% and standard error of $0.2293/\sqrt{(\text{number of cycles})}\%$.

The large delays occurred on the average once every 11.6 hours with a duration of 1.31 hours per delay. The mean delay percentage obtained was 11.3% and standard error of $0.223/\sqrt{(\text{number of days})\%}$.

For small delays, 11% mean delays was obtained at study length of 334 cycles and with 90% confidence interval of ±2%. For large delays, 11.3% mean delay was obtained at a study length of 140 days and with 90% confidence interval of ±3.68%.

The reason for a smaller confidence interval in small delays than large delays is the accuracy of detailed time study data. It is easy to collect sufficient data to accurately estimate the percentage of small delays within an acceptable standard error.

TIME STUDY TECHNIQUES COMPARISON

Both shift level and detailed time study were able to detect treatment differences. There was no difference between means of two methods. Standard error obtained from regression was used to predict confidence intervals. Finally it lead to determining study length.

Shift level results show that for each additional day on the corridor the production is decreased by 0.373 per cycles per hour. In detailed time study, yarding distance, lateral distance, and carriage height were important variables. The significant variables common to shift and detailed are heavy treatment, light with openings treatment, logs, and tops. The variable called shift level days (number of days on corridor) is the equivalent of yarding distance in detailed time study. The detailed regression had five more significant variables which were not measured in shift level. The detailed regression explained 47.7% of the variation compared to 59.5% in the shift regression.

The standard error for the shift level study is higher than that in detailed and hence the shift level 95% confidence interval of predicted cycle/hour is 6.5 times wider than that of detailed. This demonstrates the relative precision of detailed time study compared to shift level study. These also show how long a study would need to be conducted in order to reduce the confidence band width to an acceptable level. The study shows that to attain a width of ± 0.20 cycles/hour a detailed time study would be run for 4 days and a shift level could achieve this level only after 171 working days. It is also possible to estimate confidence interval corresponding to a known number of days of study.

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APPENDICES

APPENDIX A

EXAMPLE OF HARVESTING UNIT LAYOUT FOR SKYLINE, TRACTOR, AND MECHANIZED SITES

Figure A.1. Example of skyline corridor layout (Walkthin, unit 89, light with openings) (Kellogg et al., 1997).

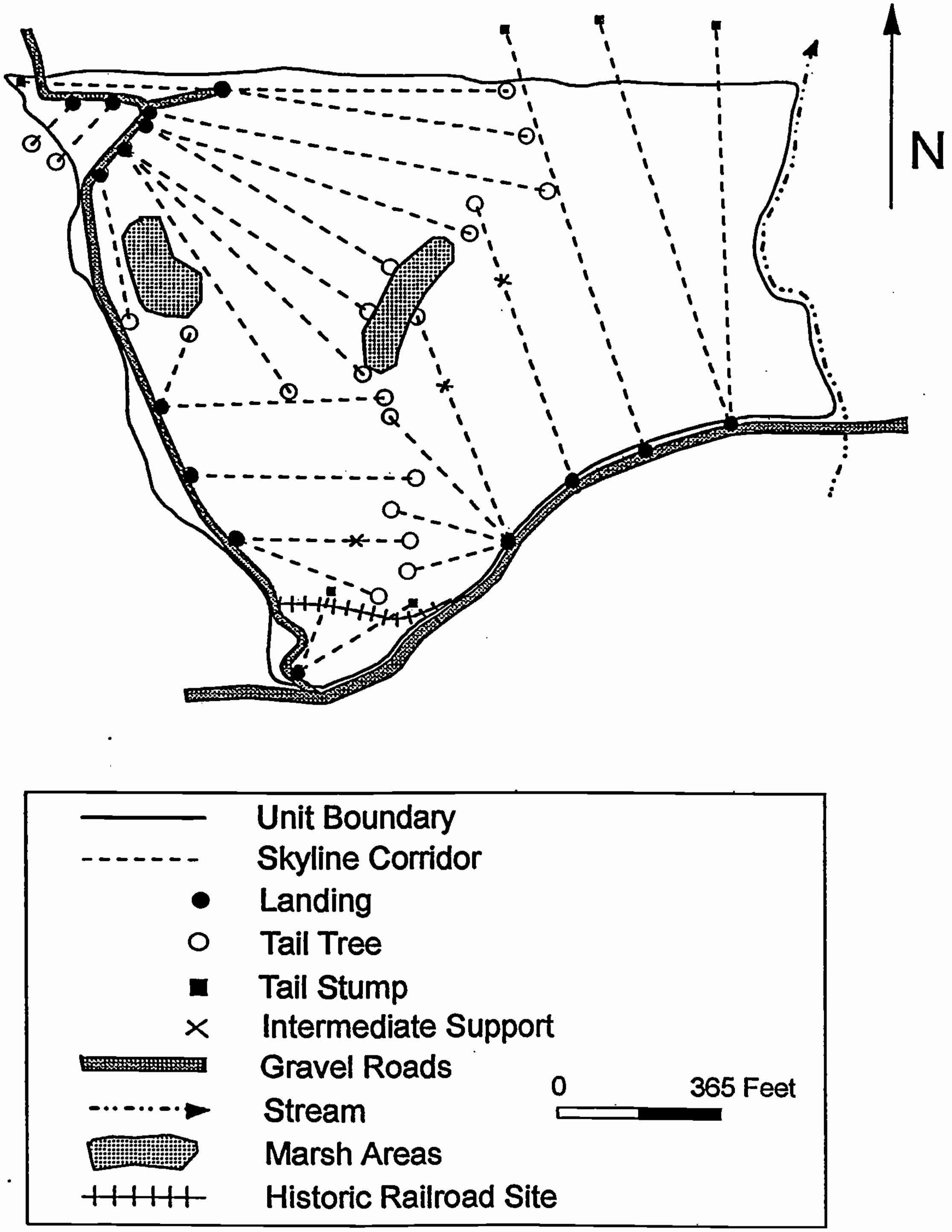


Figure A.2. Example of light with openings thin treatment unit (Walkthin, unit 89) (Kellogg et al., 1997).

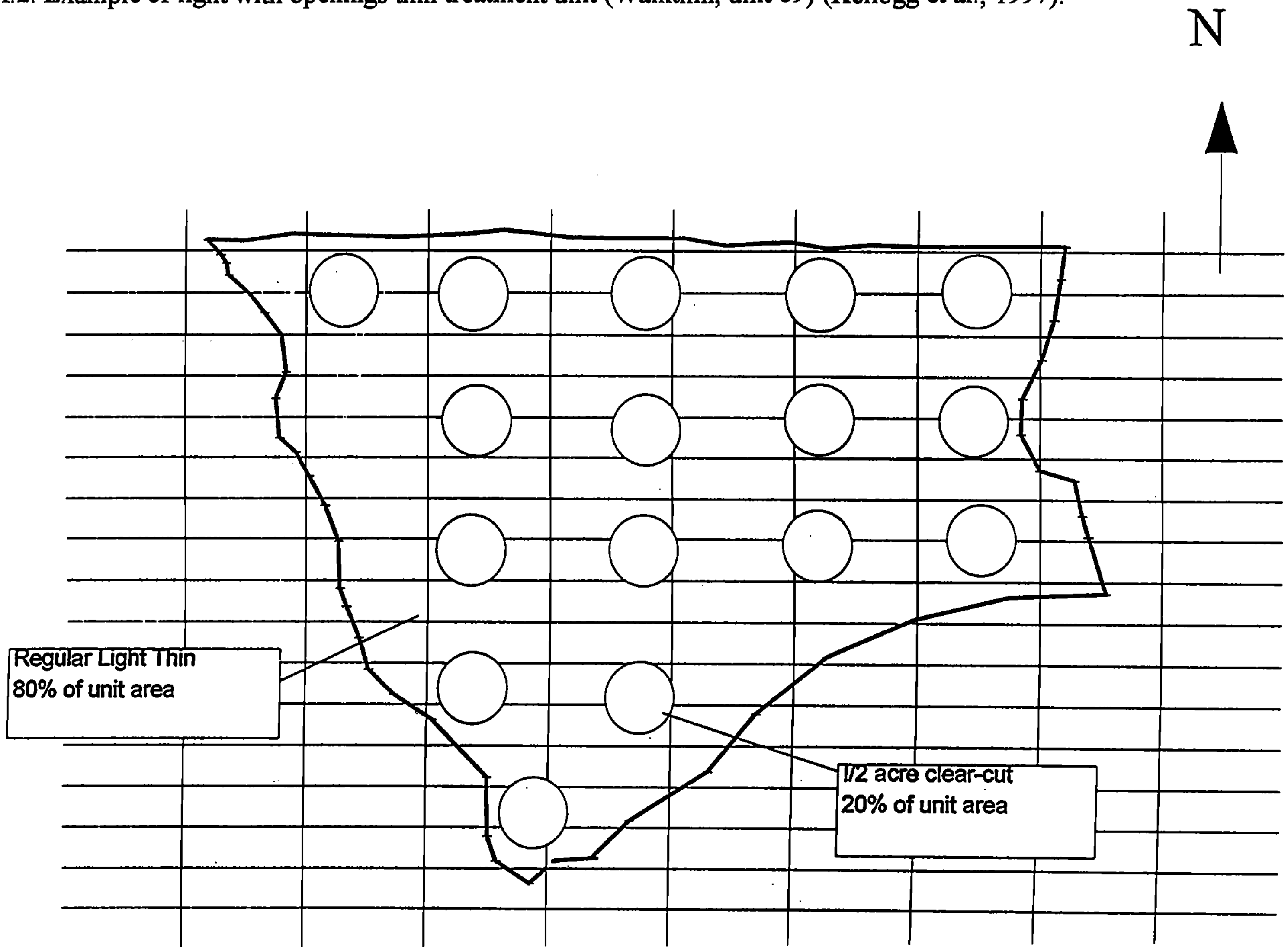


Figure A.3. Example of skid trail layout (Tapthin, unit 3, light) (Kellogg, et al., 1997)

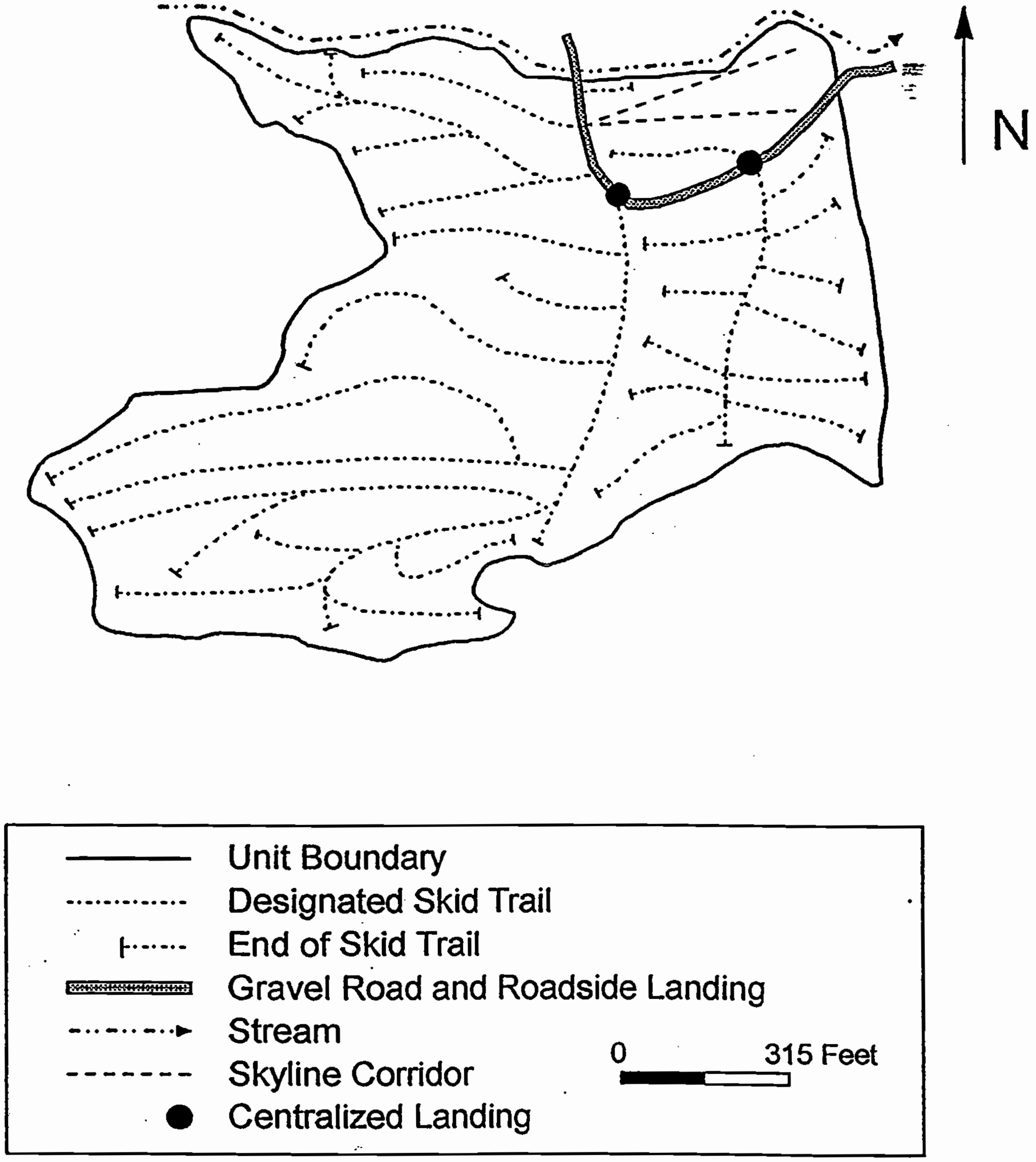
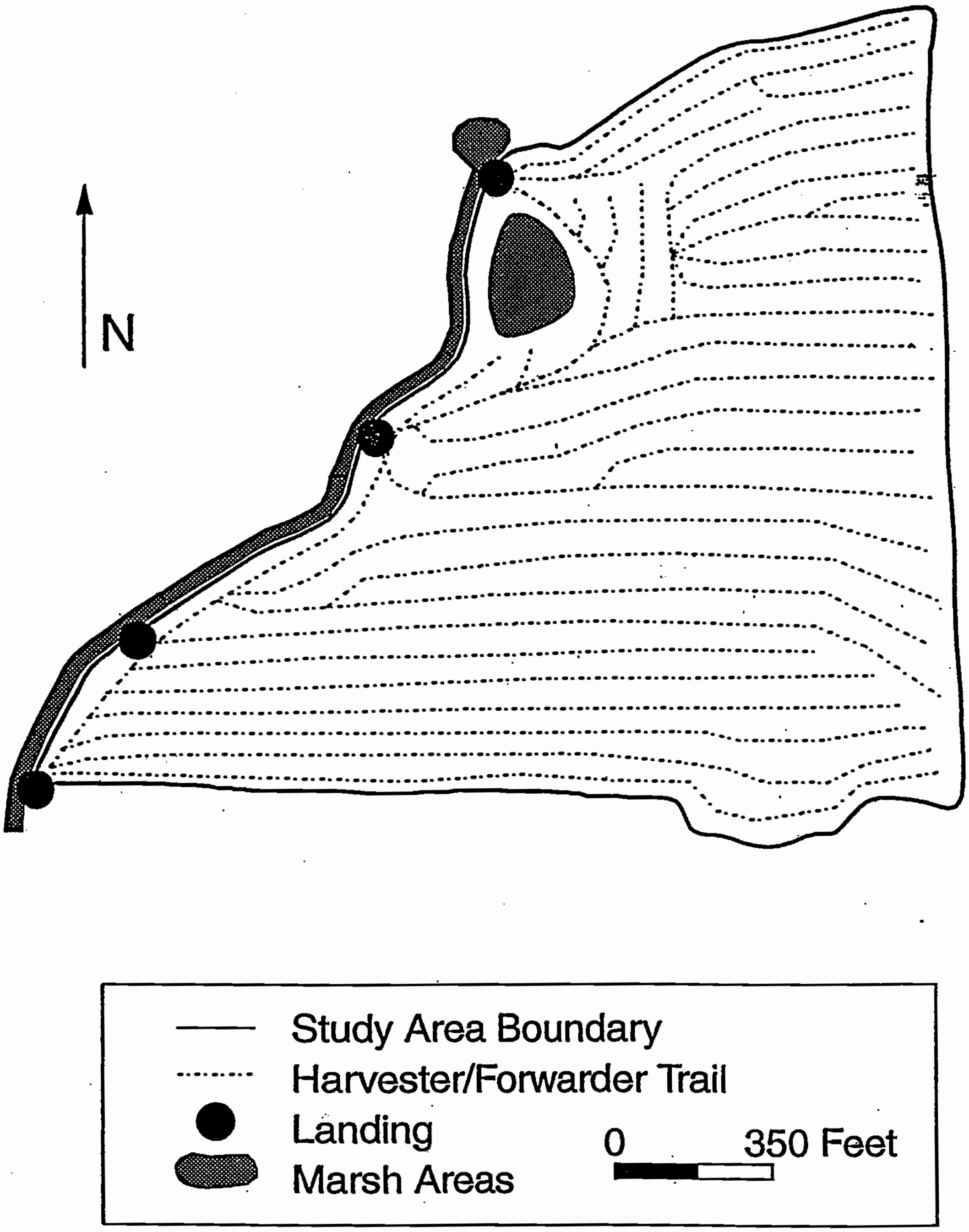


Figure A.4. Example of harvester and forwarder trail layout (Flatthin, unit 81, heavy) (Kellogg, et al., 1997).



APPENDIX B

STUDY SITES AND STAND DESCRIPTION BEFORE AND AFTER COMMERCIAL THINNING

Table B.1. Study sites and stand description[1] before and after commercial thinning in Metric unit.

Sale Name (Ranger District)	Treatment	Unit #	Logging System	Unit area (ha)	Before harvest Mean dbh (cm)	Before harvest trees /ha	Harvest cu.m. /ha	AED (m)	Slope (%)	Harvest season
Walk Thin (Oakridge)	Light	85	Skyline	22.3	24.4	576	158	174	5-80	Summer
	Lt. w/Open.	86	Skyline	14.2	26.4	524	251	174	5-80	Sum/fall
	Heavy	88	Skyline	19.0	27.7	417	209	174	5-80	Winter
	Lt. w/Open.	89	Skyline	16.2	26.4	524	149	174	5-80	Sum/fall
Tap Thin (Blue River)	Heavy[2]	1	Tractor	11.7	27.7	445	145	211	0-40	Fall
	Heavy	1	Skyline	7.7	27.7	445	147	186		Sum/fall
	Light	3	Tractor	13.4	24.9	642	213	211	0-40	Sum/fall
	Light	3	Skyline	24.3	24.9	642	213	186		Sprg/sum
	Lt. W/Open.[2]	4	Tractor	1.6	27.2	568	165	211	0-40	Fall
	Lt. w/Open.	4	Skyline	12.9	27.2	568	184	186		Summer
Mill Thin 1 (McKenzie)	Light	1	Tractor	32.4	30.0	494	222	163	0-15	Summer
	Light[3]	1	Skyline	4.8	30.0	494	222	114	0-50	Summer
	Heavy	2	Tractor	6.9	30.0	482	250	163	0-15	Summer
	Heavy[3]	2	Skyline	27.9	30.0	482	250	114	0-50	Fall/wintr
Mill Thin 2 (McKenzie)	Lt. w/Open.	4	Tractor	19.8	30.0	484	279	163	0-15	Fall
Flat Thin (Oakridge)	Heavy	81	Mech.[4]	20.2	26.9	824	351	280[5]	0-20	Sum/fall
	Lt. w/Open.	82	Mech.	38.9	30.0	529	296	280[5]	0-20	Fall/wintr
	Light	84	Mech.	31.9	29.2	647	279	280[5]	0-20	Fall

[1] The stand characteristics were determined from a cruise of trees greater than 13 cm. dbh. Commercial thinning occurred between December of 1993 and March 1997 (Han, 1997).

[2] Combined together to form one data set

[3] Combined together to form one data set

[4] Mechanized

[5] (OUTDIST+LOADDIST+INDIST)/2 = 280 m.

Table B.2. Study sites and stand description[1] before and after commercial thinning in English unit

Sale Name (Ranger District)	Treatment	Unit #	Logging System	Unit area (ac)	Before harvest Mean dbh (in)	Before harvest trees /ac	Harvest ccf /ac	AED (ft)	Slope (%)	Harvest season
Walk Thin (Oakridge)	Light	85	Skyline	55	9.6	233	22.5	570	5-80	Summer
	Lt. w/Open.	86	Skyline	35	10.4	212	35.8	570	5-80	Sum/fall
	Heavy	88	Skyline	47	10.9	169	29.8	570	5-80	Winter
	Lt. w/Open.	89	Skyline	40	10.4	212	20.7	570	5-80	Sum/fall
Tap Thin (Blue River)	Heavy[2]	1	Tractor	29	10.9	180	20.7	693	0-40	Fall
	Heavy	1	Skyline	19	10.9	180	21.0	610		Sum/fall
	Light	3	Tractor	33	9.8	260	30.4	693	0-40	Sum/fall
	Light	3	Skyline	60	9.8	260	30.4	610		Sprg/sum
	Lt. w/Open.[2]	4	Tractor	4	10.7	230	23.5	693	0-40	Fall
	Lt. w/Open.	4	Skyline	32	10.7	230	26.3	610		Summer
Mill Thin 1 (McKenzie)	Light	1	Tractor	80	11.8	200	31.7	534	0-15	Summer
	Light[3]	1	Skyline	12	11.8	200	31.7	375	0-50	Summer
	Heavy	2	Tractor	17	11.8	195	35.7	534	0-15	Summer
	Heavy[3]	2	Skyline	69	11.8	195	35.7	375	0-50	Fall/wintr
Mill Thin 2 (McKenzie)	Lt. w/Open.	4	Tractor	49	11.8	196	39.8	534	0-15	Fall
Flat Thin (Oakridge)	Heavy	81	Mech.[4]	50	10.6	334	50.2	920[5]	0-20	Sum/fall
	Lt. w/Open.	82	Mech.	96	11.8	214	42.3	920[5]	0-20	Fall/wintr
	Light	84	Mech.	79	11.5	262	39.8	920[5]	0-20	Fall

[1] The stand characteristics were determined from a cruise of trees greater than 5 in. dbh. Commercial thinning occurred between December of 1993 and March 1997 (Han, 1997).

[2] Combined together to form one data set

[3] Combined together to form one data set

[4] Mechanized

[5] (OUTDIST+LOADDIST+INDIST)/2 = 920 ft.

APPENDIX C

EQUIPMENT AND CREW FOR SKYLINE YARDING, TRACTOR SKIDDING, AND MECHANIZED (CUT-TO-LENGTH) SYSTEMS

Table C.1. Skyline yarding operation equipment and crew

	Yarder	Loader	Skidder	Carriage	Crew
Walkthin	• Koller K501 trailer mounted 3-drum yarder • 33 ft. tower • Skyline drum, 1640 ft. of 0.75 in diameter wire rope • Mainline drum 1965 ft. of 0.5 in diameter wire rope	Thunderbird 634 crawler-mount loader	1982 Cat D-7G	Eaglet mechanical slackpulling carriage	5-person crew • Yarder engineer • Chaser • Loader operator • Rigging slinger • Hook tender
Tapthin	• Koller K501 trailer mounted 3-drum yarder • 33 ft. tower • Skyline drum, 1640 ft. of 0.75 in diameter wire rope • Mainline drum 1965 ft. of 0.5 in diameter wire rope	Koehring 266L crawler-mount loader	John Deere grapple skidder	Eaglet mechanical slackpulling carriage	7-person crew • Yarder engineer • Chaser • Loader operator • Rigging slinger • Hook tender • 2 choker setter
Millthin	• Madill 071 mobile 4-drum yarder • 70 ft. tower • Skyline drum, 2000 ft. of 0.87 in diameter wire rope • Mainline drum, 2200 ft. of 0.5 in. diameter wire rope • Haulback drum, 4400 ft. of 0.5 in. diameter wire rope.	Case 125B Crawler mount-loader		Danebo mechanical slackpulling carriage	5-person crew • Yarder engineer • Chaser • Loader operator • Rigging slinger • Hook tender

Table C.2. Tractor skidding operation equipment and crew

	Tractor	Loader	Crew
Tapthin	• John deere 550 crawler with Winch line	• Koehring 6630 tract-mount loader	• Chaser • Loader operator • Tractor operator
Millthin 1	• Case 550 crawler with winch line	• Case 125B tract-mount loader	• Chaser • Loader operator • Tractor operator
Millthin 2	• Case 550 crawler with winch line	• Case 125B tract-mount loader	• Chaser • Loader operator • Tractor operator

Table C.3. Harvester-forwarder operation equipment and crew

	Harvester	Forwarder	Crew
Flatthin	• 2618 Timberjack (tracked carrier) with south fork squirt boom • Waterous 762b hydraulic harvesting head	• 1210 Timberjack 8-wheel drive • Bogie tracks used	• Harvester operator • Forwarder operator

APPENDIX D

EXAMPLE OF COSTS CLACULATION WITH STANDARD ERROR TERMS USING LOGGING PRODUCTION AND COSTS FLOW CHART

Steps in skyline yarding costs calculation with standard error terms

Step 1 Effective Hour

Total delay = 15.5%
Effective hour = 60(1-0.155)
= 50.7 min/hour

Standard Error of Effective Hour

From delay simulation (Chapter 4),
Small delay standard error = 2%
Large delay standard error = 3%
Combined standard error =

$$\sqrt{2^2 + 3^2}$$

$$= 3.6\%$$

3.6% of 60 min = 2.16 min/hour

Step 2 Cycle Time

Total delay free cycle time
= 5.17 min/cycle

Standard Error of Cycle Time

= Std. Error of Y estimate / √(n)
= 0.7413 min/cycle /√(937)
= 0.024 min/cycle

Step 3 Cycles per Hour

= Effective hour /Cycle time
= 50.7 (min/hr) / 5.17 (min/cycle)
= 9.80 cycle/hr

Standard Error of cycles/hour

$$\sigma^2_{\frac{A}{B}} = \left(\frac{\mu_A}{\mu_B}\right)^2 \left[\frac{\sigma_A^2}{\mu_A^2} + \frac{\sigma_B^2}{\mu_B^2}\right]$$

$$= \left(\frac{50.7}{5.17}\right)^2 \left[\frac{(2.16)^2}{(50.7)^2} + \frac{(.024)^2}{(5.17)^2}\right]$$

$$= 0.176 \text{ cycles}^2 / \text{hr}^2$$

$$\sigma_{\frac{A}{B}} = 0.420 cycles / hr$$

Step 4 Cycle Size

= 1.83 logs (0.1814 ccf/log)
+ 1.62 tops (0.0625 ccf/top)
+ 1.27 fibers (0.025 ccf/fiber)
= 0.461 ccf/cycle

Standard error of cycle size

$$\sigma^2_{Log+Top+Fiber} = \left[\frac{1.12 \log s}{\sqrt{937}}(0.1865 ccf / \log)\right]^2$$

$$+ \left[\frac{1.24 tops}{\sqrt{937}}(0.0625 ccf / top)\right]^2$$

$$+ \left[\frac{1.23 fibers}{\sqrt{937}}(0.0215 ccf / fiber)\right]^2$$

$$\sigma_{Log+Top+Fiber} = \sqrt{(0.0068)^2 + 0.0025)^2 + (0.00086)^2}$$

$$= 0.0073 ccf / cycle$$

Step 5 Production

= (Cycles/hour)(ccf/cycle)
= (9.8 cycles/hr.)(0.461 ccf/cycle)
= 4.514 ccf/hour

Step 6 Owning and Operating Costs

= $ 218.62/hour

Step 7 Net to Gross Timber Scale

= 0.99

Step 8 Average Yarding Costs

$$= \frac{\text{Owning and operating costs}}{\text{(Production)(Net to Gross scale)}}$$

$$= \frac{\$\ 218.62\text{/hour}}{(4.514\ \text{ccf/hour})(0.99)}$$

= $ 48.92/ccf

Step 9 Rd/Lndg. Change, Move in/Out Costs

= $ 6.62/ccf

Step 10 Average Costs

= Yarding Costs + Rd/lndg. Chng. costs

= $ (48.92+6.62)/ccf

= $ 55.54/ccf

Standard Error of Production

$$\sigma_{AB}^2 = \mu_A^2\sigma_B^2 + \mu_B^2\sigma_A^2 + \sigma_B^2\sigma_A^2$$

$$= (9.80)^2(0.0073)^2 + (0.461)^2(0.420)^2 + (0.0073)^2(0.420)^2$$

$$\sigma_{AB} = \sqrt{0.041} = 0.202 ccf / hour$$

Step 11 95% Confidence Interval

$$= \frac{\text{Owning and operating costs}}{\{\text{Prod} \pm 1.96(\text{std.err.})\}(\text{net\_gross})} + \text{Rd/lndg.}$$

$$= \frac{\$\ 218.62\text{/hour}}{\{4.514\ \text{ccf/hour} \pm 1.96(0.206)\}(0.99)} + \$6.62\text{/ccf}$$

= $ 51.51/ccf, $ 60.35/ccf.

APPENDIX E

COST TABLES FOR YARDING, SKIDDING, AND MECHANIZED OPERATIONS

Table E.1a. Cost table for Walkthin yarding operation in Metric unit

Treatment	Effective Hour (min/hr)	Delay free Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Op Costs ($/hr)	Net to Gross	Average Yarding Costs ($/$m^3$)	Rd/Land Ch/Move in/out ($/$m^3$)	Average Total Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$)	95% Upper C.L. ($/$m^3$)
Light Thin	50.7 (2.16)	5.17 (0.02)	9.80 (0.420)	1.306 (0.021)	12.79 (0.583)	218.62	0.99	17.26	2.336	19.60	18.18	21.30
Heavy Thin	50.7 (2.16)	4.23 (0.02)	11.98 (0.515)	1.219 (0.021)	14.598 (0.674)	218.62	0.99	15.13	2.336	17.46	16.21	18.97
Light w/ Opening	50.7 (2.16)	4.68 (0.02)	10.83 (0.465)	1.264 (0.021)	13.677 (0.629)	218.62	0.99	16.15	2.336	18.48	17.15	20.08

Table E.1b. Cost table for Walkthin yarding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (ccf/cycle)	Production (ccf/hr)	Own/ Oper. Costs ($/hr)	Net to Gross	Average Yarding Costs ($/ccf)	Rd/Land Ch/Move in/out ($/ccf)	Average Total Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	50.7 (2.16)	5.17 (0.02)	9.80 (0.420)	0.461 (0.0073)	4.514 (0.206)	218.62	0.99	48.92	6.62	55.54	51.51	60.35
Heavy Thin	50.7 (2.16)	4.23 (0.02)	11.98 (0.515)	0.430 (0.0073)	5.151 (0.238)	218.62	0.99	42.87	6.62	49.49	45.93	53.77
Light w/ Opening	50.7 (2.16)	4.68 (0.02)	10.83 (0.465)	0.446 (0.0073)	4.826 (0.222)	218.62	0.99	45.76	6.62	52.38	48.60	56.90

[1] Road and landing change, move in and out, and setup and tear down total cost per unit.
The figures within parentheses are standard error of respective term.

Table E.2a. Cost table for Tapthin yarding operation in Metric unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/ Oper. Costs ($/hr)	Net to Gross	Average Yarding Costs ($/$m^3$)	Rd/Land Ch/Move in/out[1] ($/$m^3$)	Average Total Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$)	95% Upper C.L. ($/$m^3$)
Light Thin	46.5 (2.16)	4.33 (0.02)	10.73 (0.501)	1.729 (0.021)	18.55 (0.895)	271.97	0.99	14.81	4.03	18.84	17.55	20.38
Heavy Thin	46.5 (2.16)	4.22 (0.02)	10.01 (0.514)	1.510 (0.021)	19.48 (0.810)	271.97	0.99	16.50	4.03	20.53	19.09	22.27
Light w/ Opening	46.5 (2.16)	4.01 (0.02)	11.59 (0.541)	1.590 (0.021)	18.424 (0.893)	271.97	0.99	14.91	4.03	18.94	17.64	20.50

Table E.2b. Cost table for Tapthin yarding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles Per Hour	Cycle size Size (ccf/cycle)	Production (ccf/hr)	Own/ Oper. Costs ($/hr)	Net to Gross	Average Yarding Costs ($/ccf)	Rd/Land Ch/Move in/out ($/ccf)	Average Yarding Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	46.5 (2.16)	4.33 (0.02)	10.73 (0.501)	0.610 (0.0074)	6.546 (0.316)	271.97	0.99	41.97	11.41	53.38	49.75	57.76
Heavy Thin	46.5 (2.16)	4.22 (0.02)	10.01 (0.514)	0.533 (0.0074)	6.873 (0.286)	271.97	0.99	46.77	11.41	58.18	54.11	63.12
Light w/ Opening	46.5 (2.16)	4.01 (0.02)	11.59 (0.541)	0.561 (0.0074)	6.501 (0.315)	271.97	0.99	42.26	11.41	53.67	50.00	58.11

[1] Road and landing change, move in and out, and setup and tear down total cost per unit.

The figures within parentheses are standard error of respective term.

Table E.3a. Cost table for Millthin yarding operation in Metric unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Op Costs ($/hr)	Net to Gross	Average Yarding Costs ($/m^3)	Rd/Land Ch/Move in/out[1] ($/m^3)	Average Total Costs ($/m^3)	95% Lower C.L. ($/m^3)	95% Upper C.L. ($/m^3)
Heavy	41.2	5.61	7.34	1.655	12.15	244.88	0.99	20.36	5.60	25.96	23.80	28.71
Thin	(2.16)	(0.05)	(0.391)	(0.048)	(0.737)							

Table E.3b. Cost table for Millthin yarding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (ccf/cycle)	Production ccf/hr	Own/Op Costs ($/hr)	Net to Gross	Average Yarding Costs ($/ccf)	Rd/Land Ch/Move in/out[1] ($/ccf)	Average Total Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Heavy	41.2	5.61	7.34	0.584	4.287	244.88	0.99	57.70	15.87	73.57	67.43	81.36
Thin	(2.16)	(0.05)	(0.391)	(0.017)	(0.260)							

[1] Road and landing change, move in and out, and setup and tear down total cost per unit.
The figures within parentheses are standard error of respective term.

Table E.4a Cost table for Tapthin skidding operation in Metric unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Op Costs ($/hr)	Net to Gross	Average Total Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$))	95% Upper C.L. ($/$m^3$)
Light Thin	43.0 (2.06)	9.235 (0.116)	4.66 (0.241)	2.26 (0.031)	10.52 (0.564)	94.58	0.99	9.08	8.22	10.15
Heavy Thin	43.0 (2.16)	11.248 (0.116)	3.82 (0.196)	2.08 (0.028)	7.96 (0.422)	94.58	0.99	12.00	10.87	13.39

Table E.4b. Cost table for Tapthin skidding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (ccf/cycle)	Production ccf/hr	Own/Op Costs ($/hr)	Net to Gross	Average Skidding Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	43.0 (2.06)	9.235 (0.116)	4.66 (0.241)	0.797 (0.011)	3.712 (0.199)	94.58	0.99	25.74	23.29	28.76
Heavy Thin	43.0 (2.16)	11.248 (0.116)	3.82 (0.196)	0.735 (0.010)	2.808 (0.149)	94.58	0.99	34.02	30.82	37.96

The figures within parentheses are standard error of respective term.

Table E.5a. Cost table for Millthin 1 skidding operation in Metric unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Op Costs ($/hr)	Net to Gross	Average Total Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$)	95% Upper C.L. ($/$m^3$)
Light Thin	47.8 (2.16)	7.225 (0.094)	6.62 (0.311)	1.82 (0.034)	12.02 (0.609)	78.44	0.99	6.59	6.00	7.32
Heavy Thin	47.8 (2.16)	8.37 (0.094)	5.71 (0.266)	1.683 (0.034)	9.61 (0.487)	94.66	0.99	9.95	9.05	11.04

Table E.5b. Cost table for Millthin 1 skidding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (ccf/cycle)	Production ccf/hr	Own/Op Costs ($/hr)	Net to Gross	Average Skidding Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	47.8 (2.16)	7.225 (0.094)	6.62 (0.311)	0.641 (0.012)	4.24 (0.215)	78.44	0.99	18.69	17.00	20.75
Heavy Thin	47.8 (2.16)	8.37 (0.094)	5.71 (0.266)	0.594 (0.012)	3.392 (0.172)	94.66	0.99	28.19	25.64	31.30

The figures within parentheses are standard error of respective term.

Table E.6a. Cost table for Millthin 2 skidding operation in Metric unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Op Costs ($/hr)	Net to Gross	Average Total Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$))	95% Upper C.L. ($/$m^3$)
Light with Opening	48.3 (2.16)	8.361 (0.165)	5.78 (0.282)	1.90 (0.057)	11.00 (0.629)	78.14	0.99	7.17	6.45	8.08

Table E.6b. Cost table for Millthin 2 skidding operation in English unit

Treatment	Effective Hour (min/hr)	Cycle Time (min/cycle)	Cycles per Hour	Cycle Size (ccf/cycle)	Production ccf/hr	Own/Op Costs ($/hr)	Net to Gross	Average Skidding Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light with Opening	48.3 (2.16)	8.361 (0.165)	5.78 (0.282)	0.672 (0.02)	3.883 (0.222)	78.14	0.99	20.33	18.28	22.90

The figures within parentheses are standard error of respective term.

Table E.7a. Cost table for Flatthin Harvester operation in Metric unit

Treatment	Effective Hour (min/hr)	Delay free Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Oper Costs ($/hr)	Net to Gross	Rd/Land Ch/Move in/out ($/$m^3$)	Average Harvesting Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$)	95% Upper C.L. ($/$m^3$)
Light Thin	29.6 (2.16)	0.905 (0.0152)	32.711 (2.4529)	0.621 (0.0103)	20.302 (1.5592)	103.62	0.99	0.14	5.30	4.58	6.15
Heavy Thin	29.6 (2.16)	0.905 (0.0152)	32.711 (2.4529)	0.621 (0.0103)	20.302 (1.5592)	103.62	0.99	0.14	5.30	4.58	6.15
Light w/ Opening	29.6 (2.16)	0.963 (0.0152)	30.741 (2.2984)	0.813 (0.0133)	25.004 (1.9040)	103.62	0.99	0.14	4.33	3.74	5.02

Table E.7b. Cost table for Flatthin Harvester operation in English unit

Treatment	Effective Hour (min/hr)	Delay free Cycle Time (min/cycle)	Cycles Per Hour	Cycle size Size (ccf/cycle)	Production (ccf/hr)	Own/Oper Costs ($/hr)	Net to Gross	Rd/Land Ch/Move in/out ($/ccf)	Average Total Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	29.6 (2.16)	0.905 (0.0152)	32.711 (2.4529)	0.219 (0.0036)	7.164 (0.5502)	103.62	0.99	0.4	15.01	12.97	17.43
Heavy Thin	29.6 (2.16)	0.905 (0.0152)	32.711 (2.4529)	0.219 (0.0036)	7.164 (0.5502)	103.62	0.99	0.4	15.01	12.97	17.43
Light w/ Opening	29.6 (2.16)	0.963 (0.0152)	30.741 (2.2984)	0.287 (0.0047)	8.823 (0.6754)	103.62	0.99	0.4	12.26	10.61	14.22

[1] Road and landing change, and move in and out total cost per unit.

The figures within parentheses are standard error of respective term.

Table E.8a. Cost table for Flatthin Forwarder operation in Metric unit

Treatment	Effective Hour (min/hr)	Delay free Cycle Time (min/cycle)	Cycles Per Hour	Cycle Size (m^3/cycle)	Production (m^3/hr)	Own/Oper Costs ($/hr)	Net to Gross	Rd/Land Ch/Move in/out ($/$m^3$)	Average Forwarding Costs ($/$m^3$)	95% Lower C.L. ($/$m^3$)	95% Upper C.L. ($/$m^3$)
Light Thin	33.60 (2.16)	30.737 (0.5363)	1.093 (0.0729)	19.24 (0.6011)	21.032 (1.5499)	81.51	0.99	0.14	4.06	3.53	4.67
Heavy Thin	33.60 (2.16)	30.737 (0.5363)	1.093 (0.0729)	19.24 (0.6011)	21.032 (1.5499)	81.51	0.99	0.14	4.06	3.53	4.67
Light w/ Opening	33.60 (2.16)	41.74 (0.5363)	0.805 (0.0529)	19.24 (0.6011)	15.488 (1.1266)	81.51	0.99	0.14	5.46	4.75	6.28

Table E.8b. Cost table for Flatthin Forwarder operation in English unit

Treatment	Effective Hour (min/hr)	Delay free Cycle Time (min/cycle)	Cycles Per Hour	Cycle size Size (ccf/cycle)	Production (ccf/hr)	Own/Oper Costs ($/hr)	Net to Gross	Rd/Land Ch/Move in/out ($/ccf)	Average Forwarding Costs ($/ccf)	95% Lower C.L. ($/ccf)	95% Upper C.L. ($/ccf)
Light Thin	33.60 (2.16)	30.737 (0.5363)	1.093 (0.0729)	6.789 (0.2121)	7.421 (0.5469)	81.51	0.99	0.4	11.49	10.00	13.24
Heavy Thin	33.60 (2.16)	30.737 (0.5363)	1.093 (0.0729)	6.789 (0.2121)	7.421 (0.5469)	81.51	0.99	0.4	11.49	10.00	13.24
Light w/ Opening	33.60 (2.16)	41.74 (0.5363)	0.805 (0.0529)	6.789 (0.2121)	5.465 (0.3975)	81.51	0.99	0.4	15.47	13.45	17.79

[1] Road and landing change, and move in and out total cost per unit.
The figures within parentheses are standard error of respective term.

APPENDIX F

COSTS COMPARISON BETWEEN TREATMENTS, SITES, AND SYSTEMS USING t-TEST

Table F.1. Comparison of skyline yarding cost between treatments of Walkthin site

Treatment	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.error of difference ($/m^3)	t-stat	p-value
Light	285	19.60	0.7959				
				2.14	1.0626	2.014	0.0222
Heavy	301	17.46	0.7041				
				1.02	1.0268	0.993	0.1605
Light w/ Opening	351	18.48	0.7474				
				1.12	1.0918	1.026	0.1526
Light	285	19.60	0.7959				

Table F.2. Comparison of light thin skyline yarding cost between sites

Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.error of difference ($/m^3)	t-stat	p-value
Walkthin	285	19.60	0.7959				
				0.76	1.0745	0.707	0.2399
Tapthin	187	18.84	0.7219				

Table F.3. Comparison of heavy thin skyline yarding cost between sites

Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.error of difference ($/m^3)	t-stat	p-value
Walkthin	301	17.46	0.7041				
				3.07	1.0741	2.858	0.0022
Tapthin	208	20.53	0.8112				
				5.49	1.4944	3.633	0.0001
Millthin	229	25.96	1.2551				
				8.50	1.4391	5.906	0.0000
Walkthin	301	17.46	0.7041				

Table F.4. Comparison of light with opening thin skyline yarding cost between sites

Site	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.error of difference ($\$/m^3$)	t-stat	p-value
Walkthin	351	18.48	0.7474	0.46	1.0445	0.440	0.3300
Tapthin	276	18.94	0.7296				

Table F.5. Comparison of tractor skidding cost between treatments of Tapthin site

Treatment	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.error of difference ($\$/m^3$)	t-stat	p-value
Light	67	9.08	0.4823	2.92	0.8077	3.615	0.0002
Heavy	63	12.00	0.6403				

Table F.6. Comparison of tractor skidding cost between treatments of Millthin1 site

Treatment	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.error of difference ($\$/m^3$)	t-stat	p-value
Light	90	6.59	0.3367	3.36	0.6092	5.515	0.0000
Heavy	87	9.95	0.5076				

Table F.7. Comparison of light thin tractor skidding cost between sites

Site	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.error of difference ($\$/m^3$)	t-stat	p-value
Tapthin	67	9.08	0.4923	2.49	0.5559	4.479	0.0000
Millthin 1	90	6.59	0.3367				

Table F.8. Comparison of heavy thin tractor skidding cost between sites

Site	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.error of difference ($\$/m^3$)	t-stat	p-value
Tapthin	63	12.00	0.6403	2.05	0.8171	2.509	0.0066
Millthin 1	87	9.95	0.5076				

Table F.9. Comparison of light thin skyline yarding costs between sites at different distance.

AED (m)	Site	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.err. of diff. ($\$/m^3$)	t-stat	p-value
100	Walkthin	285	18.16	0.7347	1.15	0.9712	0.844	0.1995
	Tapthin	187	17.01	0.6352				
300	Walkthin	285	24.08	1.0051	0.19	1.3964	0.136	0.4459
	Tapthin	187	23.89	0.9694				

Table F.10. Comparison of heavy thin skyline yarding costs between sites at different distance.

AED (m)	Site	Sample size (n)	Mean cost ($\$/m^3$)	Std.err. of cost ($\$/m^3$)	Difference of means ($\$/m^3$)	Std.err. of diff. ($\$/m^3$)	t-stat	p-value
100	Walkthin	301	15.35	0.6090	2.48	0.9105	2.724	0.0039
	Tapthin	208	17.83	0.6787	7.77	1.4134	5.497	0.0000
	Millthin	229	25.60	1.2398				
300	Walkthin	301	21.37	0.8826	3.77	1.3608	2.770	0.0029
	Tapthin	208	25.14	1.0357	2.90	1.7316	1.675	0.0473
	Millthin	229	28.04	1.3877				

Table F.11. Comparison of light with opening thin skyline yarding costs between sites at different distance

AED (m)	Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.err of diff. ($/m^3)	t-stat	p-value
100	Walkthin	351	16.59	0.6637	0.59	0.9474	0.623	0.2667
	Tapthin	276	16.00	0.6760				
300	Walkthin	351	22.61	0.9388	1.14	1.4111	0.808	0.2097
	Tapthin	276	23.75	1.0536				

Table F.12. Comparison of Flatthin harvesting and forwarding costs between treatments

Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.error of difference ($/m^3)	t-stat	p-value
Heavy	292	12.00	0.4429	1.46	0.7293	2.002	0.0292
Light w/ Opening	376	13.46	0.5794				

Table F.13. Comparison of light thin extraction costs between Tapthin tractor and Flatthin forwarder sites at different distance.

AED (m)	Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.err. of diff. ($/m^3)	t-stat	p-value
100	Forwarder	31	6.14	0.4541	2.29	0.6458	3.546	0.0003
	Tractor	67	8.43	0.4592				
300	Forwarder	31	6.84	0.5051	3.77	0.7627	4.943	0.0000
	Tractor	67	10.61	0.5714				

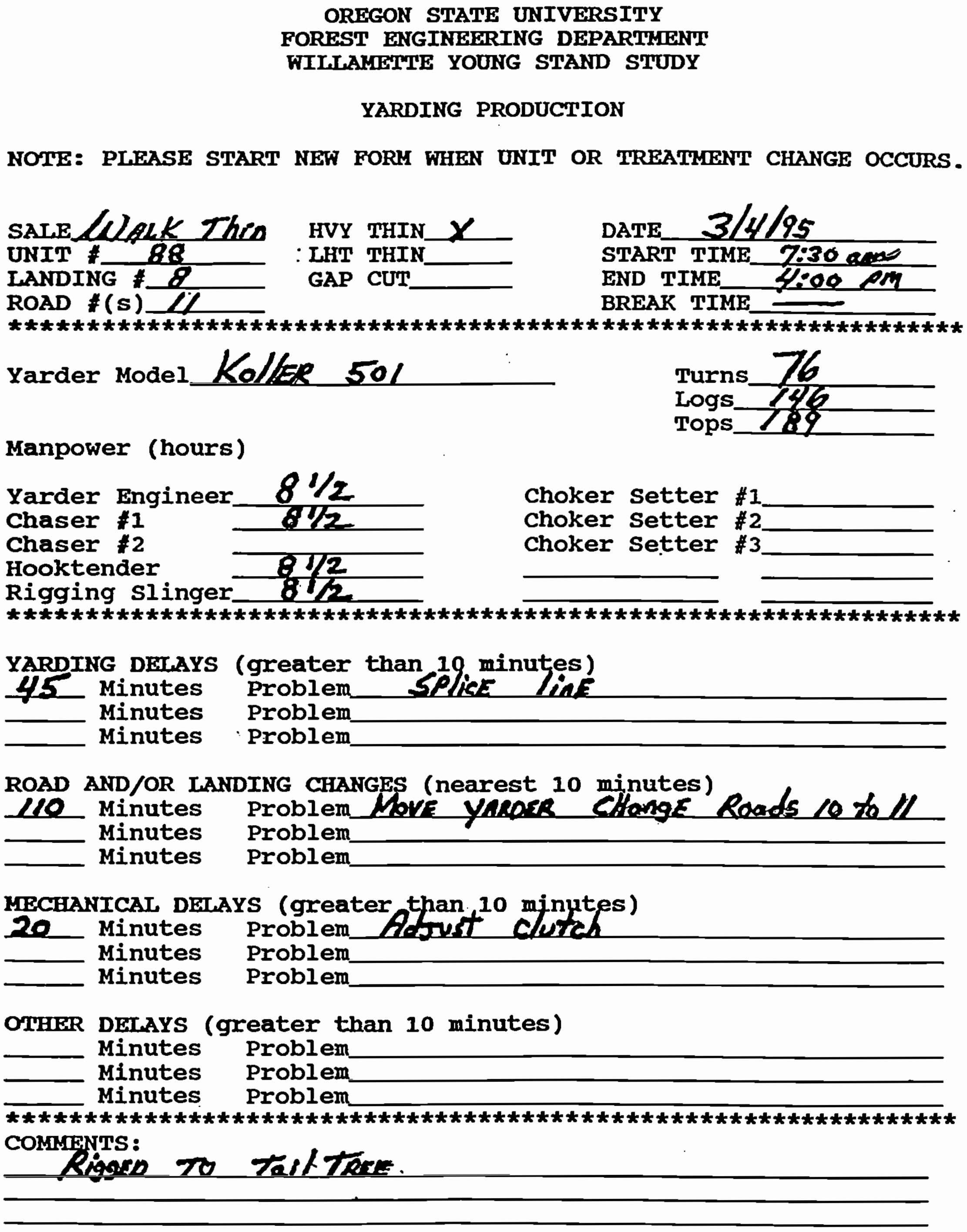
Table F.14. Comparison of light with opening thin extraction costs between Millthin 2 tractor and Flatthin forwarder sites at different distance.

AED (m)	Site	Sample size (n)	Mean cost ($/m^3)	Std.err. of cost ($/m^3)	Difference of means ($/m^3)	Std.err. of diff. ($/m^3)	t-stat	p-value
100	Forwarder	33	8.56	0.6326	2.86	0.7191	3.977	0.0000
	Tractor	66	5.70	0.3418				
300	Forwarder	33	9.26	0.6837	0.27	0.8701	0.310	0.3786
	Tractor	66	9.53	0.5383				

APPENDIX G

SHIFT LEVEL AND ACTIVITY SAMPLING DATA RECORDING FORMS

Figure G.1 Shift level skyline yarding recording form



OREGON STATE UNIVERSITY
FOREST ENGINEERING DEPARTMENT
WILLAMETTE YOUNG STAND STUDY

YARDING PRODUCTION

NOTE: PLEASE START NEW FORM WHEN UNIT OR TREATMENT CHANGE OCCURS.

SALE WALK Thin
UNIT # 88
LANDING # 8
ROAD #(s) 11

HVY THIN X
LHT THIN
GAP CUT

DATE 3/4/95
START TIME 7:30 am
END TIME 4:00 pm
BREAK TIME ——

****

Yarder Model KollER 501

Turns 76
Logs 146
Tops 189

Manpower (hours)

Yarder Engineer 8 1/2
Chaser #1 8 1/2
Chaser #2
Hooktender 8 1/2
Rigging Slinger 8 1/2

Choker Setter #1
Choker Setter #2
Choker Setter #3

****

YARDING DELAYS (greater than 10 minutes)
45 Minutes Problem SPLICE LINE
Minutes Problem
Minutes Problem

ROAD AND/OR LANDING CHANGES (nearest 10 minutes)
110 Minutes Problem MOVE YARDER Change Roads 10 to 11
Minutes Problem
Minutes Problem

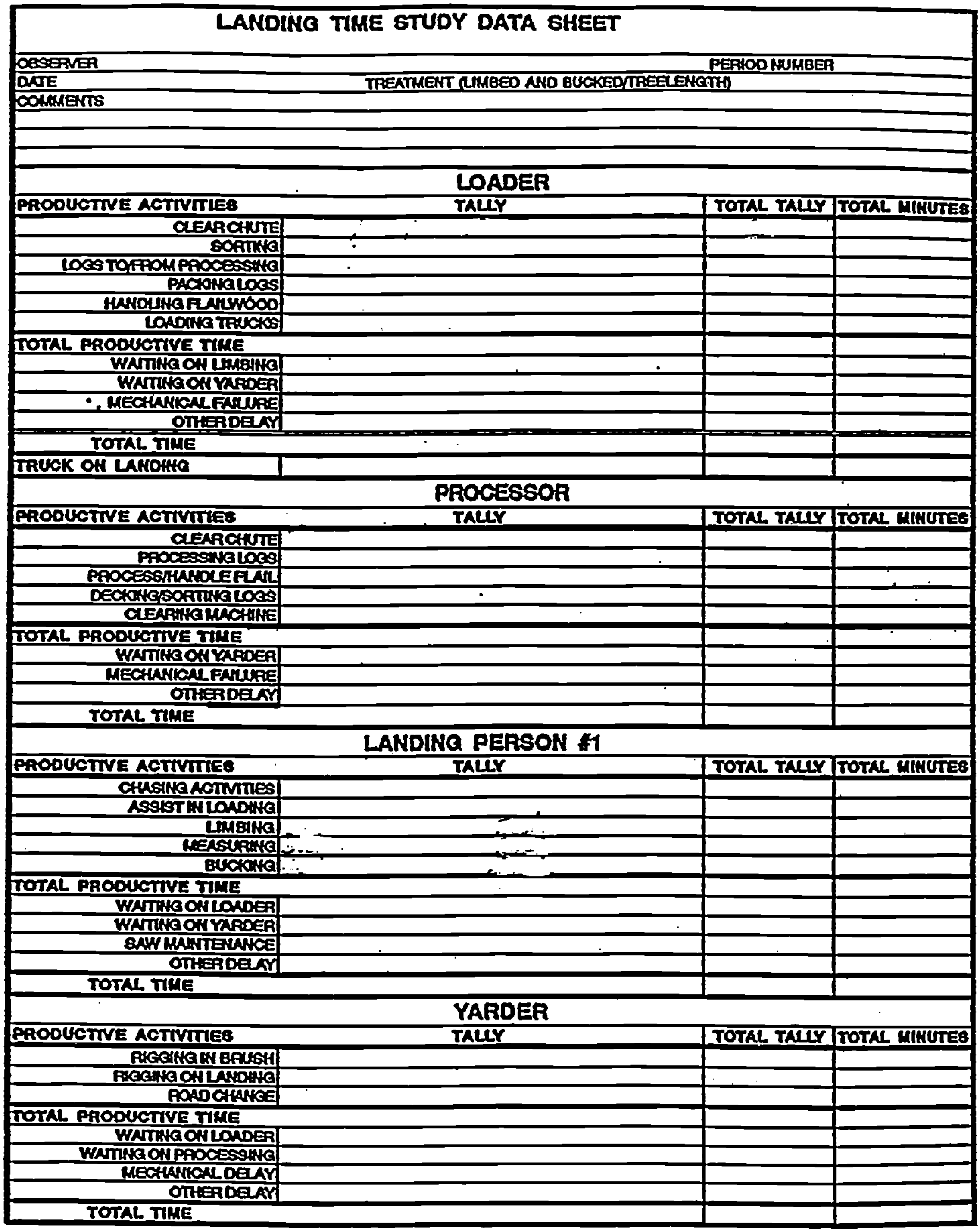
MECHANICAL DELAYS (greater than 10 minutes)
20 Minutes Problem Adjust clutch
Minutes Problem
Minutes Problem

OTHER DELAYS (greater than 10 minutes)
Minutes Problem
Minutes Problem
Minutes Problem

****

COMMENTS:
RiggED TO TAil TREE.

Figure G.2. Activity sampling form



LANDING TIME STUDY DATA SHEET

OBSERVER PERIOD NUMBER
DATE TREATMENT (LIMBED AND BUCKED/TREELENGTH)
COMMENTS

LOADER

PRODUCTIVE ACTIVITIES	TALLY	TOTAL TALLY	TOTAL MINUTES
CLEAR CHUTE			
SORTING			
LOGS TO/FROM PROCESSING			
PACKING LOGS			
HANDLING FLAILWOOD			
LOADING TRUCKS			
TOTAL PRODUCTIVE TIME			
WAITING ON LIMBING			
WAITING ON YARDER			
MECHANICAL FAILURE			
OTHER DELAY			
TOTAL TIME			
TRUCK ON LANDING			

PROCESSOR

PRODUCTIVE ACTIVITIES	TALLY	TOTAL TALLY	TOTAL MINUTES
CLEAR CHUTE			
PROCESSING LOGS			
PROCESS/HANDLE FLAIL			
DECKING/SORTING LOGS			
CLEARING MACHINE			
TOTAL PRODUCTIVE TIME			
WAITING ON YARDER			
MECHANICAL FAILURE			
OTHER DELAY			
TOTAL TIME			

LANDING PERSON #1

PRODUCTIVE ACTIVITIES	TALLY	TOTAL TALLY	TOTAL MINUTES
CHASING ACTIVITIES			
ASSIST IN LOADING			
LIMBING			
MEASURING			
BUCKING			
TOTAL PRODUCTIVE TIME			
WAITING ON LOADER			
WAITING ON YARDER			
SAW MAINTENANCE			
OTHER DELAY			
TOTAL TIME			

YARDER

PRODUCTIVE ACTIVITIES	TALLY	TOTAL TALLY	TOTAL MINUTES
RIGGING IN BRUSH			
RIGGING ON LANDING			
ROAD CHANGE			
TOTAL PRODUCTIVE TIME			
WAITING ON LOADER			
WAITING ON PROCESSING			
MECHANICAL DELAY			
OTHER DELAY			
TOTAL TIME			

APPENDIX H

DESCRIPTION OF ACTIVITY SAMPLING

DESCRIPTION OF ACTIVITY SAMPLING

Activity sampling is the third method of time study data collection in the Willamette young stand project. In this report, a description of activity sampling from Walkthin skyline yarding site is used as an example. It was done with a stopwatch simultaneously with the detailed time study data collection and one person was engaged for this purpose. The activity sample was designed in such a way that one data collection period of activity sample is equal to 10 skyline yarding cycles or approximately 1 hour. These 1 hour periods repeated at random intervals, several times during a week. Time interval between sample observations was 20 second. That is, each 20 seconds the activities of the operations were recorded. The data collection form for activity sample is shown in Appendix G (Figure G.2). Finally, percentage of time for each activity and for each of the machines or operations including productive, non productive, and delay times were determined.

Description of landing activities

This is an example of landing activities in Walkthin unit 85 (Miller, 1998). The landing crew consisted of a yarding engineer, a loader operator, and a chaser. Additionally, there was a delimbing machine which required no operator.

Once a cycle had been brought in, the chaser discontinued limbing to unhook the next cycle.

The loader cleared the cycle from the chute once it finished with sorting activities. The loader sorted logs into log piles or onto a truck, pulled pieces with limbs through the delimber, sorted a few pieces to be delimbed or bucked, and sorted small pieces into a fiber pile. The loader kept the landing very orderly and with no obstacles to the various activities. In this case he had considerable idle time.

The yarding engineer unhooked turns on the few occasions that the chaser was away assisting final loading of trucks or performing other duties off the landing. There was a very good flow of material through these landing activities. Although there were often wait time and/or idle time when one activity interfered with the other.

Data analysis, results and discussion

The percent of the time spent in each activity category were calculated. The data was first sorted into scheduled time such as productive time and non productive time. Then productive time was divided into different activities of production. The percent activities of chaser and loader are shown with pie charts in Figure H.1.

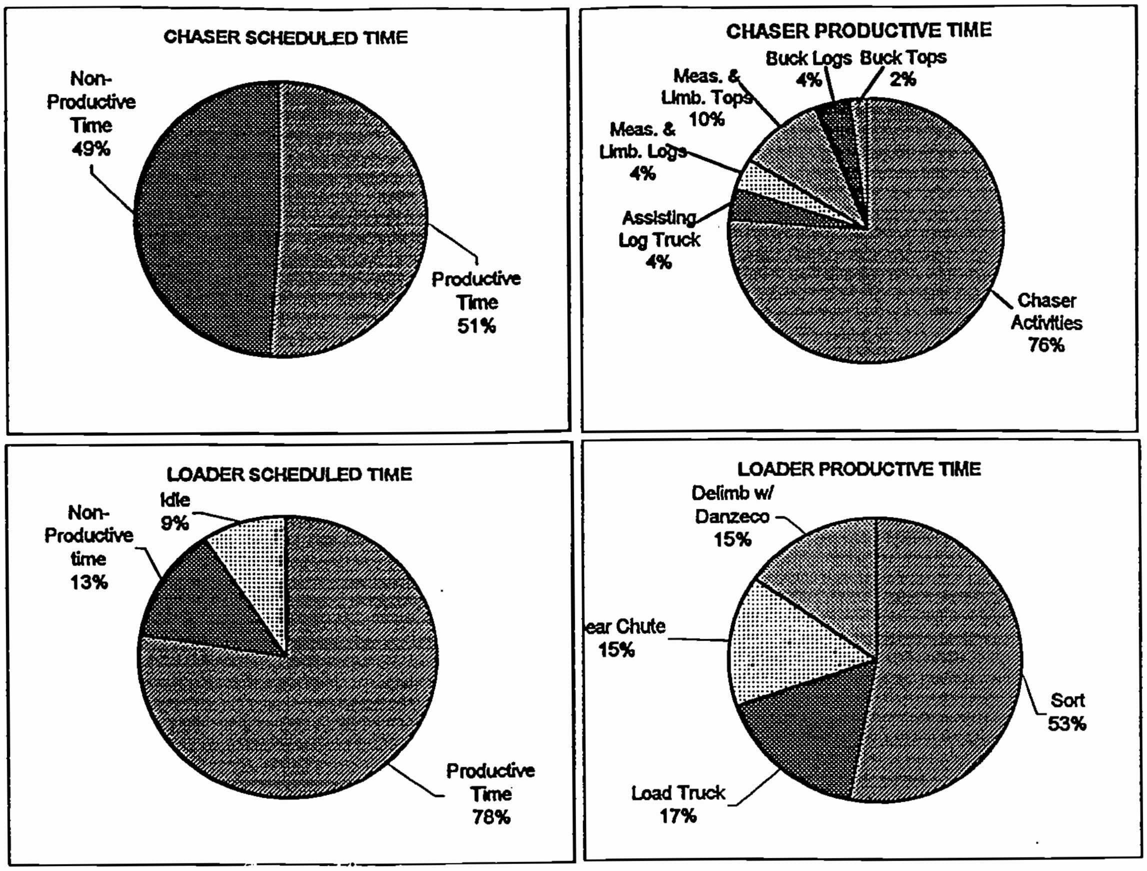
The yarder activities were not included in the chart because yarder was the one which rarely had wait time or delay time. The analysis showed that yarder had 97% productive time and only 3% non-productive time.

The chaser had 51% productive and 49% unproductive time. Out of productive time, the chaser was involved 76% for its routine activities and the remaining part of the productive time he spent assisting log truck, measurement, limb, and bucking.

The loader had 78% productive and 22% idle and unproductive time. The loader operator spent his productive time in sorting (53%), delimbing (15%), loading truck (17%), and clear chute (15%).

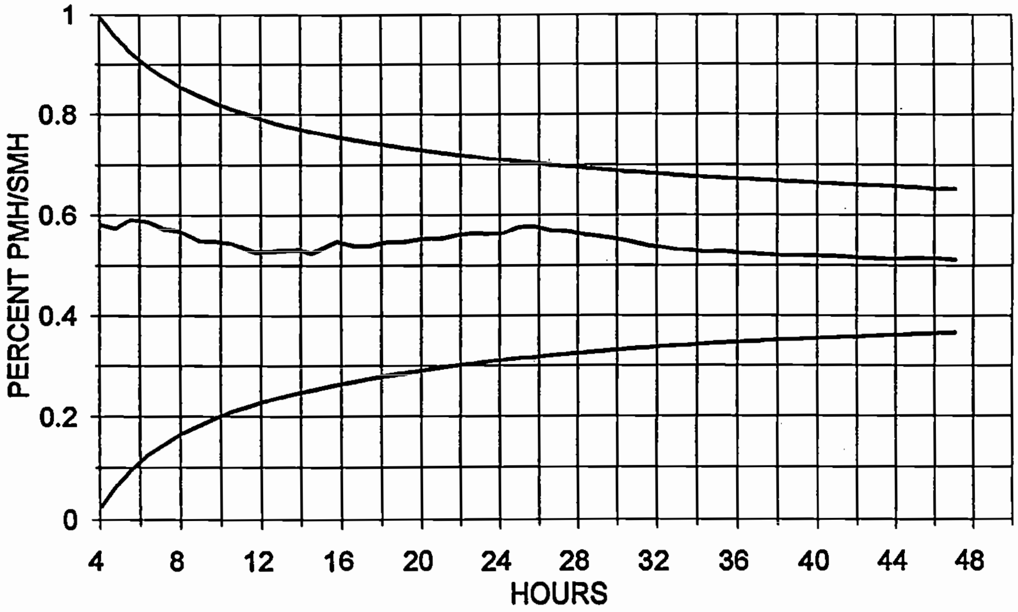
Among the three activities, chaser is the least productive. All the activities were analyzed for predicting estimate of percent utilization ((pmh/smh)*100) over period of time (hour). The percent cumulative average of pmh/smh along with 95% confidence interval were plotted for all activities in Walkthin. As an example the chaser activities plot is shown in Figure H.2. The chaser activity sample of Walkthin site yarding operation show that for 48 hours of data collection, the mean utilization is estimated to

Figure H.1. Percent activities of equipment and process



be 50% and its range of variation between 37.5% and 65% at a ninety-five percent confidence level.

Figure H.2. Percent utilization over time



Strengths and weaknesses of activity sampling

The advantage of activity sampling method are: it is a one person job, allows different activities to be evaluated simultaneously, and measures percentage of time for each activity. It is an easy method to learn and thus the training period for a data collector is very short. It is therefore a moderate cost data collection method. Moreover, the nature of the data collected in this method is unique and neither shift nor detailed time study method can measure these interaction percentages.

The disadvantages of activity sampling method are: observational intervals and the work cycle may coincide, important events occurring between observations or intervals could be missed, it may take high number of observations, and the activity sampling method of data collection is mentally fatiguing.

Scope of the future study

The present study method for collecting activity sampling data is appropriate for complementing detailed time study and shift level study. But at this stage we cannot compare activity sampling with the other two methods because the productive elements of cycle time were not timed. If a comparison were desired the activity sampling could be designed to collect data compatible with detailed time study data.

SUMMARY AND CONCLUSION OF ACTIVITY SAMPLING

The advantage of the activity sampling method are: it is a one person job, allows different activities to be evaluated simultaneously, and measures percentage of time for each activity. It is an easy method to learn and thus the training period for a data collector is short. It is, therefore, a moderate cost data collection method. Moreover, the nature of the data collected in this method is unique and neither shift nor detailed time study method can measure these interaction percentages.

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