AN ABSTRACT OF THE PAPER OF

Robert A. Wilson for the degree of Master of Forestry

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Title: A Productivity Study and Machine Selection Technique for Rubber Tired Skidders in Tasmania, Australia

Abstract approved: Redacted for Privacy
Darius M. Adams

Time study data was collected for two horsepower classes of rubber tired skidders from field operations controlled by Associated Pulp and Paper Mills, Ltd., Tasmania, Australia. A wide range of site and logging conditions were used to produce both production per hour and cycle time predictive equations.

The resultant equations were used for machine selection, on a cost and production basis, the quantification of current problems and as a planning tool for predicting the composition of the future machine pool. The selection technique was applied to the two horsepower classes studied here, plus a FMC 210CA skidder. The results indicate that the high horsepower skidder class provided no production advantage despite higher owning and operating costs. For the FMC 210CA only those high production sites provided production costs similar to the rubber tired skidders.

Two factors affecting productivity, but beyond machine-site interactions were addressed in this study, namely operator ability/machine efficiency and production quotas. The former was applied during equation formulation to produce an operator/machine adjusted equation.

The latter was shown to be significant in machine cost considerations, and the management of field operations with regard to site logging potential.

The study suggests that the current forest inventory practice be adjusted to include those site factors found to effect logging potential. Also, that similar studies on a wide range of skidding machinery be conducted to provide a broad base for machine selection and comparison.

A Productivity Study and Machine Selection Technique for Rubber Tired Skidders in Tasmania, Australia

by

Robert A. Wilson

A PAPER

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Finally, the author expresses his thanks and appreciation for the continued support and encouragement from his parents, Dr. Robert Wilson and Mrs. Margery Wilson, and Ms Patricia Bustamante, necessary in the preparation of such a paper.

The merit of originality is not novelty; it is sincerity. The believing man is the original man; he believes for himself not for another.

Thomas Carlyle

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INTRODUCTION

The logging portion of wood procurement represents a significant proportion of total wood supply costs. As such, it is essential to understand the underlying processes involved, to ensure economically sound and efficient decision making. This study concentrates on log retrieval methods, commonly called log skidding or yarding, as employed by Associated Pulp and Paper Mills, Ltd. (APPM). The objective is to develop predictive equations for production per hour and work cycle time, for two horsepower classes of rubber tired skidders, over a range of site and logging factors found in Tasmania, Australia. A method of quantifying skidder operator performance or machine efficiency is proposed that reduces variability in the original predictive equations due to above or below average operator ability or machine efficiency.

In general, the estimated equations will find application in machine comparison and selection, cost analyses and planning functions. This study uses the equations, together with cost data to illustrate machine selection decisions and comparisons, within the range of site and logging conditions studied. The comparisons involve the same two horsepower skidder groups used in this study, plus additional production data from another machine type outside this study.

In the overall planning function, the estimated equations suggest the need to reorganize the existing forest inventory system, to include not only standing volume information, but also those significant site factors found to affect logging potential. It would also appear feasible to develop a predictive model containing all current machine types involved in log retrieval, and incorporate it into long-term planning procedures regarding the necessary machine pool combination to meet expected future requirements. The complete model will be necessarily complex as developments such as tree harvesters, feller-bunchers, forwarders and a variety of machine sizes have not only necessitated more elaborate analytical approaches, but also envelop a diversity of site factors affecting logging potential.

In the logging operations of APPM, production quotas are commonly set to provide some management control over harvesting operations and wood deliveries to the mills. Hence, application of the predictive equations is not complete without some reference to the influence of imposed (management, contract, mill limits, etc.) production restrictions or quotas on log retrieval costs, and subsequent machine selection, economies of scale, operation-site production balances, and the profit potential of individual operations. This study graphically demonstrates the influence of such production quotas, and provides a method for adjusting machine cost-production data to produce a quota-adjusted machine cost per unit production.

The application of these predictive equations in machine selection and operations management has necessitated some discussion on the decision criteria for machine selection plus a review of current operation status within the study bounds. Background information regarding the study relevance and environment has also been provided to demonstrate the role and importance of such a decision making technique. The study indicates that, based on production and cost considerations, incorrect machine selection has occurred within the logging sites studied, resulting in unnecessary expenditure on more expensive machinery where technological advantages were insufficient to meet these additional costs.

In summary, the predictive equations developed in this study, in combination with machine cost data, a revised forest inventory system, and allowances for imposed production restrictions, will improve management practice and policy decisions with respect to machine selection and operations control. The technique is applicable to current decision making and long-term planning. Extensions of the study would provide an analytical tool consisting of similar predictive equations for a wide range of machinery. This would allow prediction of the required machine pool contents, present and future logging costs, actual standing volume available to present and future machine pools, and the early identification or confirmation of likely problem areas with regard to production rates and costs.

STUDY LOCATION AND BACKGROUND

Location

The study centers on one particular company in Tasmania, Australia (Figure 1), Associated Pulp and Paper Mills, Ltd. (APPM). The company conducts an integrated timber products operation concentrating in the northern parts of the state. Production processes include: pulp and paper, sawtimber, particleboard, plywood and woodchips. Raw materials are supplied from private, crown, state and company sources.

To add dimension, the following appears relevant. Company sales for 1977-78 were $A200.9 million ($US235.1)* (pulp and paper, 82%; timber, 18%) comprising 74,224 tonnes of pulp, 179,224 tonnes of paper and 52,340 cubic meters of timber. Employees numbered 4,851 which provided approximately 14% of the northern Tasmanian workforce. Mills are scattered across northern Tasmania (Figure 2) associated with major port facilities and outlets. This degree of commitment implies more than a cursory interest in wood procurement and harvesting, the importance of which is reflected by the significant contribution of harvesting (falling, skidding, loading and carting) costs, to total wood procurement costs, of which skidding provides approximately 25%.

To locate the study within a national context (Official Australian Yearbook, 1978; Australian Forest Resources, 1977) the Australian land mass is 7.68 million square kilometers (USA 9.60 million square kilometers) of which 5.5% (USA 22%) is considered productive forest (natural and plantation). Tasmania provides 6.4% of this productive forest land from an area representing 0.9% of Australia's total land mass (approxi-

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*Conversion rate $A1 = $US1.17 (October, 1980).

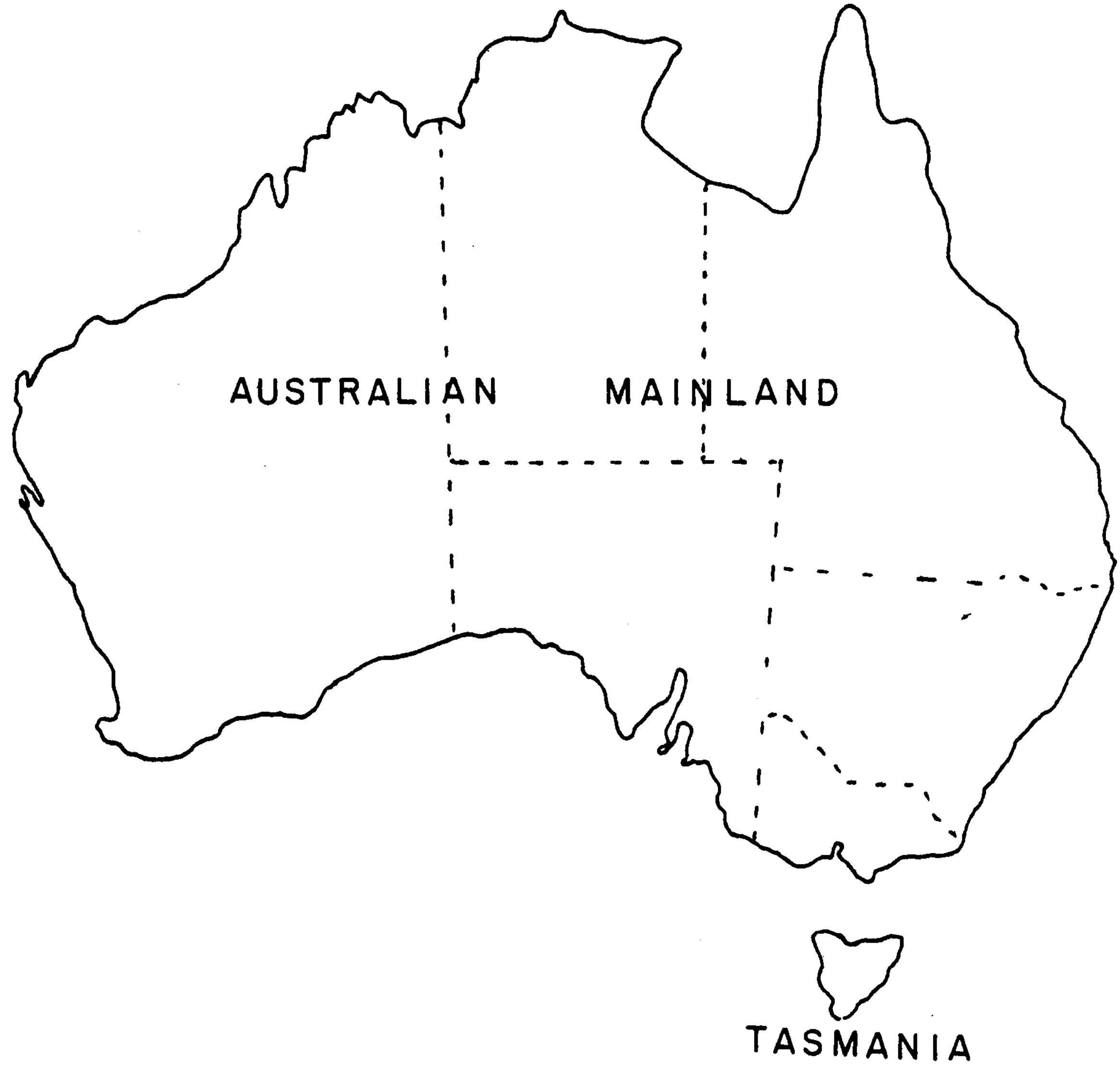


FIGURE I
THE AUSTRALIAN CONTINENT

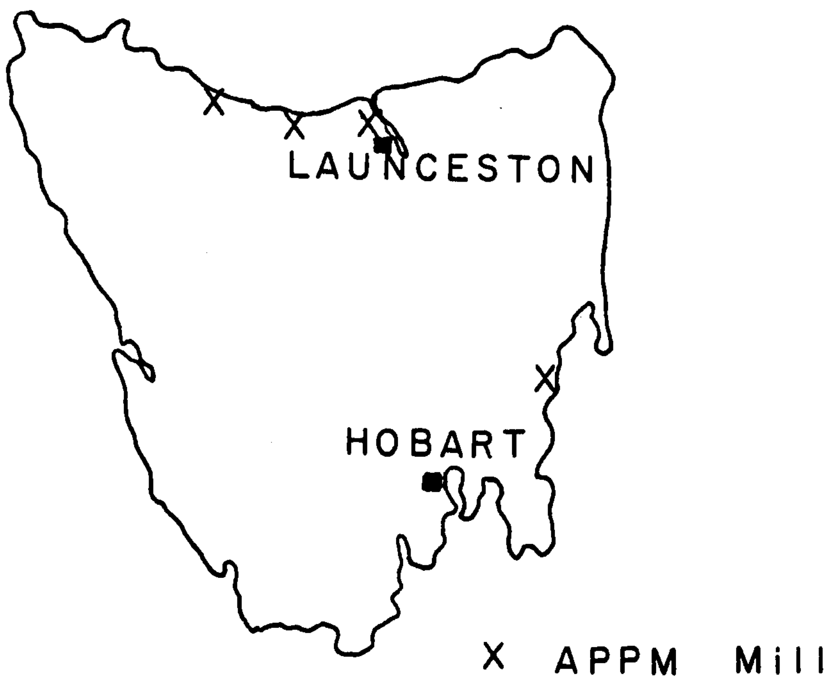


FIGURE 2

TASMANIA

mately one-third the area of Oregon). Of importance with regard to this study is that for 1975-76, 29% of national timber production was attributable to Tasmanian industry and correspondingly, 16% of forest industry employment was located in Tasmania. No imports were recorded into the state but of the sawtimber transferred between states, Tasmania contributed 34%.

The company contribution for 1975-76 was approximately six percent of sawtimber production in Tasmania, 14% of total pulp (Australia), 17% of all paper (Australia), and approximately 25% of woodchips (Australia). The company specialises in fine writing and printing papers and would hold a major share of this Australian market. These indicators imply not only the importance of Tasmania in national timber product supply but also the significant role of APPM, Ltd.

Background

While the significance of the timber industry in Tasmania is obvious, the product type and wood procurement outlook is changing. The more frequent occurrence of smaller log sizes coupled with increasingly difficult logging terrain, will have repercussions in future viability and stability of wood supply. To maintain current levels of timber production, some reliance is placed on technological advances in the timber processing function, but to supply all timber needs a major responsibility lies in maintaining continuous economic and efficient logging operations. Some steps have already been taken to broaden the range of accessible logging sites, through the company purchase of an FMC 210CA log skidder in 1978 (Wilson, Kerruish and Moore, 1980).

This study is part of an on-going company investigation into the productivity and structure within the company's logging operations. The broad objective is to isolate problem areas with respect to viability and efficiency and provide methods of rationalization within the wood procurement system.

The actual data collected for this study refers to those wood supply operations delivering to the APPM woodchip mill in N. E. Tasmania. It is of value here to outline the system of wood procurement as background to the problem and the reasons for the techniques used in data collection and result presentation.

The woodchip operation commenced in 1972 with basic wood supply sources being the Tasmanian Forestry Commission (state and crown forest), sawmill residues (field and mill non-utilisable material) and private property (e.g. agricultural land clearing, tree farms and company holdings, etc.). The company opted to contract wood supplies and there are 46 separate contractor operations today.

In most cases the operations involve clearfalling and small production units with a wide variety of machinery. An average weekly production is approximately 400 gross cubic meters and an average operation consists of one skidder, one loader, 3.5 field personnel and one log truck. There is also a contingent of sub-contractors supplying mainly the log carting function. The variety of machinery reflects the diverse origins of the contractor operations; sawmillers with heavy machinery, specialist loggers (few, but amongst the highest producers), and small contractors or farmers with light equipment and low capital investment.

For wood flow control reasons the contractors have been allocated weekly production quotas, depending on mill production requirements, available machinery, timber availability and contractor potential. These quotas are adhered to quite strictly and as such represent an additional constraint in the machine selection process and profit potential. This influence is discussed more fully later in this paper.

Before venturing into more detail, it is of value to present a general description of the forest condition to provide reader orientation.

Forest Description. In Tasmania, forest ownership classes are divided such: state and crown, 44%; national parks, 7%; private, 36%; other public, 13%. Of the established plantations, the state contributes 69%, mostly of *Pinus radiata*. A bulk of these plantations are entering the first or second thinning stage. Of the established private plantations the company probably contributes approximately 80% of which one-third are beyond 30% slope. The company relies fairly heavily on wood supply from state-controlled sources, and does so through long term agreements or Acts of Parliament (e.g. Wesley Vale Pulp and Paper Industry Act, 1961).

As regards forest composition, the most common and also preferred species, is the Eucalyptus. In coastal and low altitude areas this species can be found in association with grassland or as pure forest with a variety of genera depending on localised topography, soil type, aspect and rainfall, etc. At higher altitudes the species may also occur as pure forest or as a successional stage in a rainforest-type dominated by *Nothofagus cunninghamii*.

Eucalyptus genera are usually regarded as shade intolerant, hence the preferred silvicultural practice generally involves clear-falling, burning and sowing or planting.

The commonly occurring species include: Eucalyptus delegatensis, E. obliqua, E. viminalis, E. amygdalina, E. dalrympleana and E. regnans. Average volume per hectare is approximately 175 cubic meters (merchantable gross volume). Average heights (dominant) range from 15 meters to greater than 55 meters. Better quality trees (height and diameter) are commonly associated with higher altitude and steeper areas (although this could, in part, reflect previous logging practices of avoiding difficult areas and operating in close proximity to the mill site).

The current state of the forest is best described as "cut-over". That is, a bulk of the forested land has been selectively logged, leaving only those poorer quality stems and difficult to access areas. With the advent of clearfalling (through the wood-chip industry), and increased demand for sawtimber, those poorer quality sawlogs and previously economically inaccessible areas have become viable, extending life for the sawmilling industry. However, this increased supply has been insufficient to meet the demand, necessitating quotas on sawmill intake with further restrictions in the future. This evidence confirms the general poor nature of the standing forest, which as noted before being shade intolerant, and without suitable management can lead to stagnation and long-term decline in genetic quality. The wood-chip industry has thus provided an outlet for the poorer quality material and a means to renew the forest resource. This study then is analysing those harvesting practices involved in this woodchipping operation.

As regards planning, APPM interacts with the Tasmanian Forestry Commission on the basis of a five-year plan, which outlines future cutting units, expected volumes, roading proposals and regeneration progress. The essential item with regard to this study is that a medium already exists in which to collect and present the relevant logging potential information as part of normal forest inventory practices. Planning on private property follows a similar degree of intensity.

Soils. By far the most common type is Dolerite, characterised by a high proportion of clay, red coloration, moderate resistance to erosion and less frequently, although significantly, containing rock fragments which cause ground contact problems for machinery. Loss of traction can be a problem in very wet conditions. Second, is the Mathinna Series consisting of slates, shales and quartzites, and recognized as good winter logging areas, i.e. low erodability. Thirdly, the worst regarding potential plasticity and erodability are the granite soils. These are very sandy and as such can cause major machine wear problems, especially with the occurrence of large, subsurface granite rocks. Significant loss of traction occurs in wet conditions.

Topography. Approximately 20% of forested land is considered beyond the range of the current machine pool (slopes greater than 38%). Including the FMC 210CA this percentage could be reduced, except for the fact that much of the steeper terrain appears associated with a rocky running surface or at times a small log problem, making the viable operation of the FMC 210CA suspect.

Generally, except for localised variations, coastal logging takes place on moderate relief, but moving further inland a tiered geological structure provides a spectrum of benches, moderate to steep slopes and deep soils to rock scree.

Slopes range from zero to approximately 70% and merchantable forested land is found from above sea level to approximately 3,000 feet. Ridges tend to be long and well-defined.

Weather. Rainfall in northern Tasmania and relevant to the logging areas in question ranges from 1016 mm/annum on coastal regions to 1524 mm/annum on the higher elevation inland areas. Annual rainfall variability is low, centered in winter and producing 120-200 rain-days per annum. Average annual temperature ranges from 10°C for the logging areas in question with a summer average daily maximum-minimum of 27°C/7°C and similarly for winter, 16°C/7°C. Snowfalls in higher altitude logging areas are recorded infrequently and cause only minor disruption to annual log supply.

STUDY RELEVANCE

The author conducted surveys in January 1979 and September 1979 to provide structural, financial, sociological and trend data for background to the productivity studies. Some of the results are presented here in Table 1 and Figures 3-8. These should provide the reader with insight into the current structure of the logging operations. The salient features are:

1. The extreme diversity of machine types (Table 1).
2. Heavy purchasing both in new and second-hand machinery has taken place since 1976 (Figure 3).
3. A large proportion of the current machine pool has recorded in excess of 3,000 machine hours (Figure 4).
4. A total of 190 contractor personnel were recorded with an average age of 34.8 years (distribution skewed to the right), a current average duration of employment of 4.5 years, 10.7 years of experience, and a turnover rate of 21% per annum (extrapolated from the nine-month survey time span). Of this turnover rate, skidder operators contributed four percent and fallers eight percent (Figures 5, 6, and 7).

Further in-depth analysis of the data reveals:

1. Of the machines assigned to skidding, 64% were rubber tired, or an average of one per contractor.
2. Skidder machines tend to be purchased new.
3. Ten brands of skidder machinery were recorded with a total of 33 different sizes and designs.
4. Upturn in activity (machine purchase) after 1975 is probably due to the introduction of a 40% capital investment allowance,

Table 1. The study machine pool (Sept. 1979)

Function	Manufacturer							
	Caterpillar	International	John Deere	Clark	Franklin	Timberjack	Other	Total
Skidding	16	16	13	9	6	6	9	75
Loading	29	2	3	-	-	-	19	53
Other purpose	19	4	-	-	-	-	3	26
TOTAL	64	22	16	9	6	6	31	154
<u>Skidder Type Analysis</u>								
Skidding (total)	16	16	13	9	6	6	9	75
Rubber tired	2	10	12	7	6	6	5	48
Other	14	6	1	2	0	0	4	27

CONTRACTOR MACHINE DATA

PURCHASE DATE

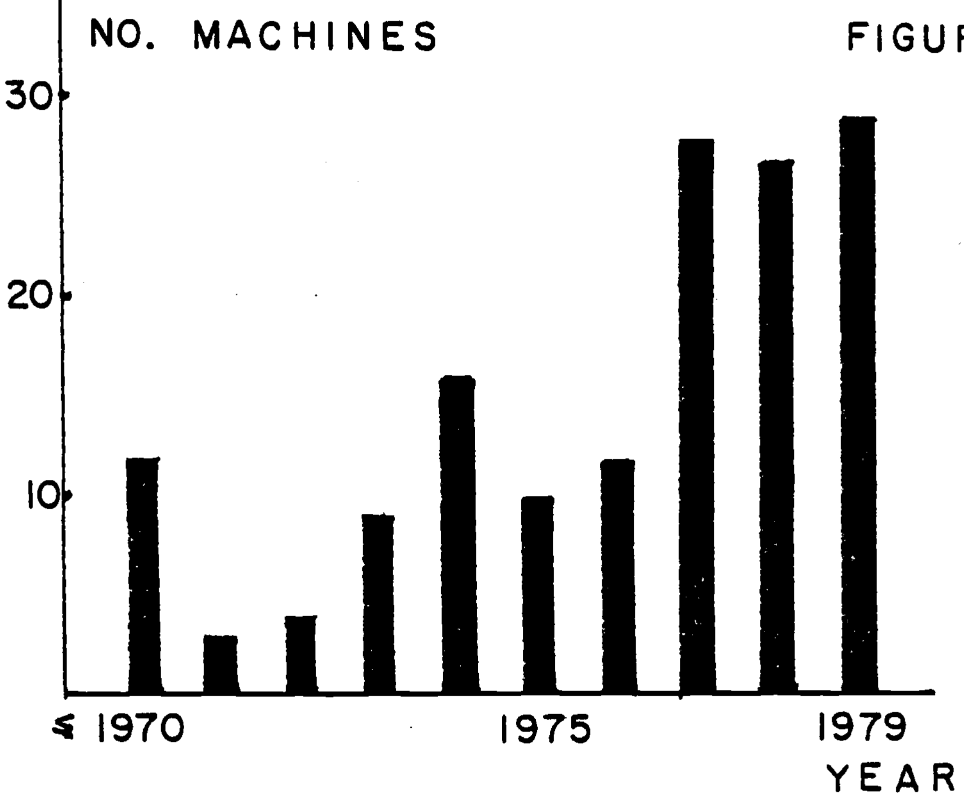


FIGURE 3

MACHINE HOURS

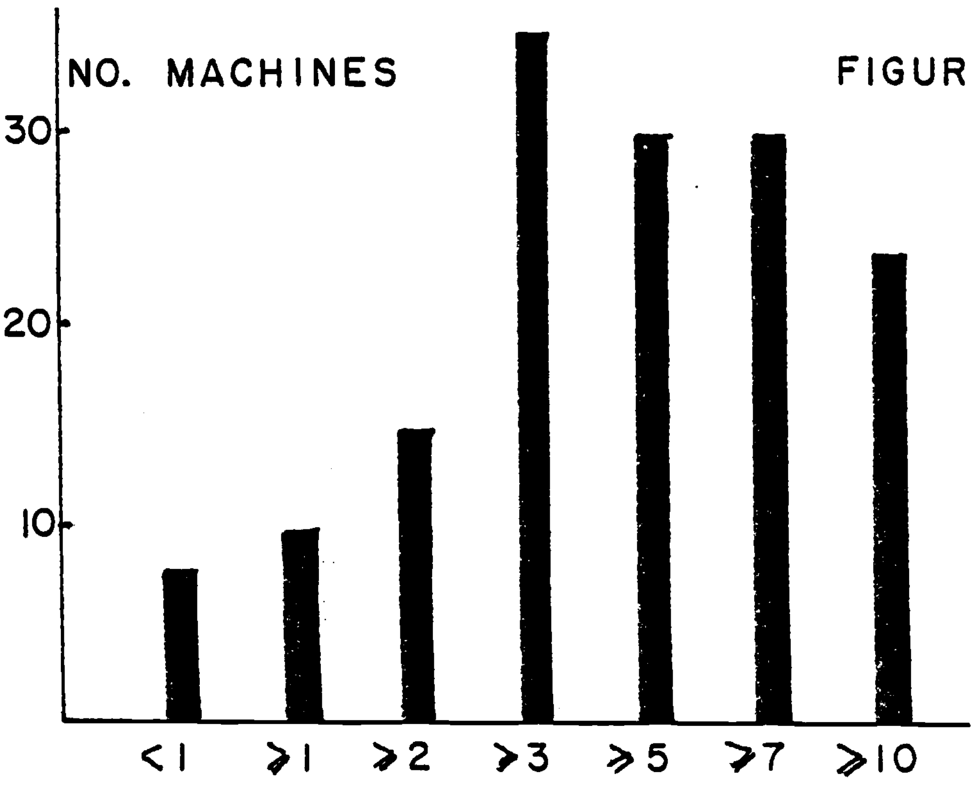
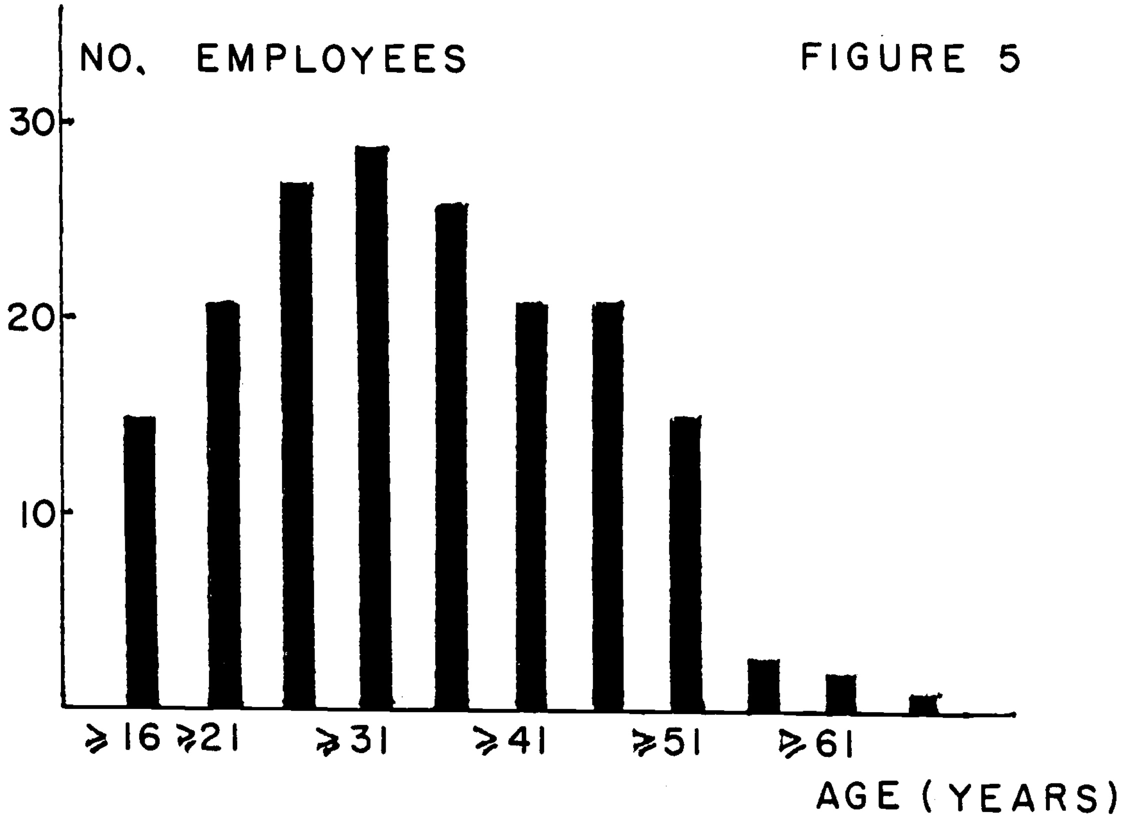


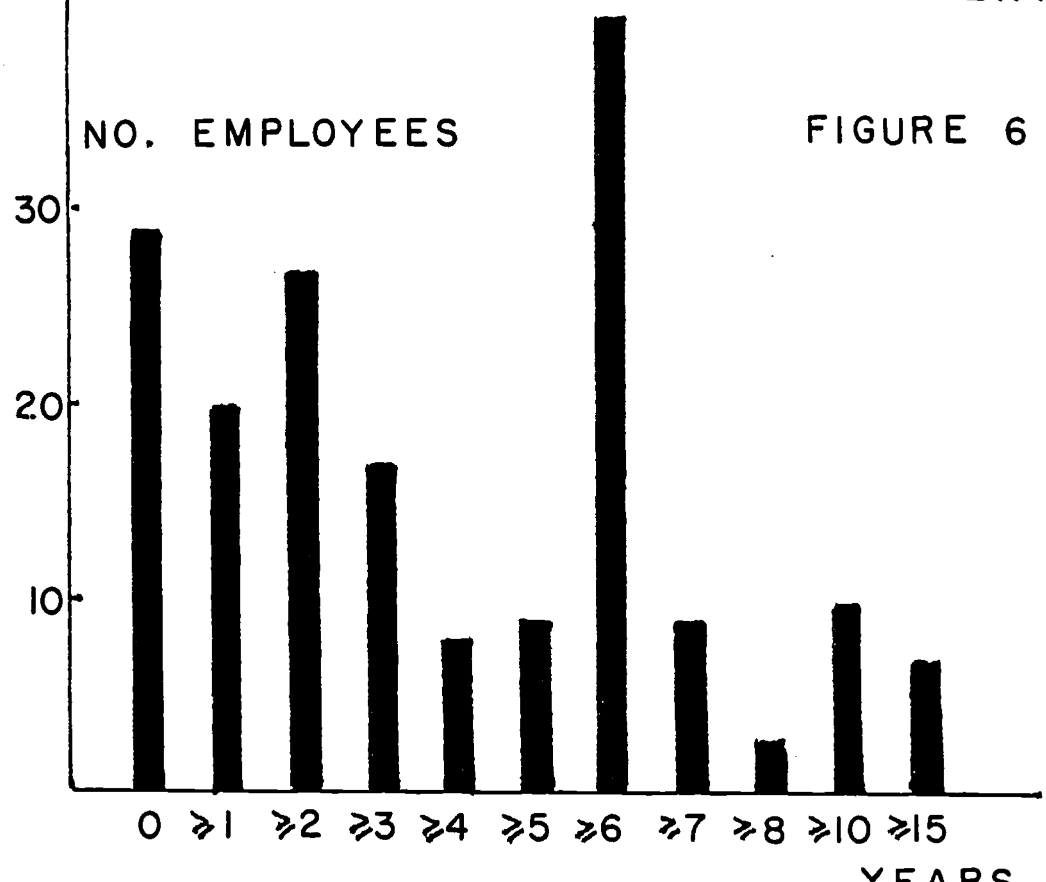
FIGURE 4

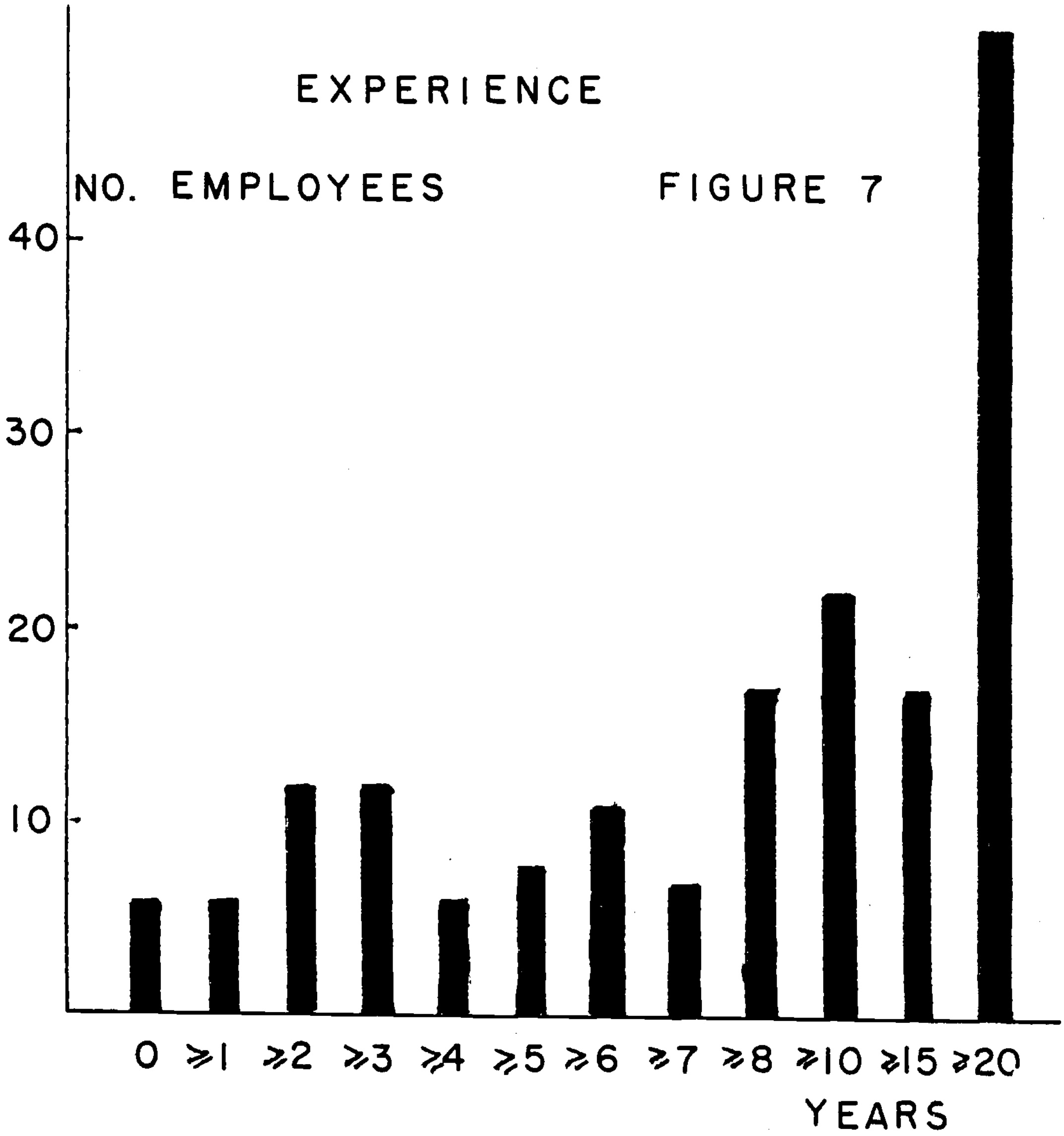
CONTRACTOR EMPLOYEE DATA

AGE DISTRIBUTION



CURRENT LENGTH OF EMPLOYMENT




EXPERIENCE
NO. EMPLOYEES
FIGURE 7
40
30
20
10
0
≥1
≥2
≥3
≥4
≥5
≥6
≥7
≥8
≥10
≥15
≥20
YEARS

plus an increased log requirement.

The structure is obviously inherently complex as an analytical base, particularly when trying to identify contractor costs and machine-site interactions plus provide general machine cost, performance and selection information. However, the company plays a significant role in contractor operations through payments, production quota setting and guidance regarding management and equipment selection. Hence, it is essential that an in-depth knowledge of logging systems be maintained to ensure a smooth flow of wood to the company mills and continued contractor viability.

Beyond this analytical base, two significant problems regarding field operations have been encountered and have added to the necessity and urgency for the proposed study. These appear common problems throughout today's logging industry, namely an increasing occurrence of small log sizes and more difficult logging terrain. Both these factors are fundamental to the resultant logging costs and as such it is essential to correctly select that machine type and logging system most appropriate to maintain viability and efficiency.

It should be noted from the survey information that the contractor machinery pool reflects the easy nature of the current logging terrain, i.e. relatively flat, non-prohibitive ground conditions, a supply of winter logging areas (stable soils) and reasonable log size and density per hectare. However, it is expected that terrain beyond current machine pool capability (e.g., lack of winter logging areas, rocky ground conditions, steep slopes, etc.) will become more evident in the future with repercussions for wood supply. For example, as previously noted, it is expected that of the state and crown forest available to the company, approximately 20% is beyond present machine capability (greater than 38% slope). To provide a relatively smooth supply of logs, the company has accepted that early introduction of steep and difficult terrain is essential to avoid a sudden and intolerable level of difficult logging in the future. Evidence of the problem is already apparent in the field where contractor's equipment has been found wanting in conditions of steep terrain, small log size, or rocky ground conditions, in small localised areas within current clearfalling units. The result has been inconvenience and hardship for contractors, plus disruption to the planning process.

Broadly speaking, the problem involves ensuring that the machine pool remains in context with current and future requirements. The solution involves establishing techniques for estimating logging difficulty, evaluating machine performance, and combining the two in planning procedures, to provide long-term estimates of machine requirements, production rates and logging costs. This solution falls into the realm of the proposed model which can now be restated; to develop predictive equations, to provide some decision making ability with respect to machine selection, cost analyses and planning.

THE MACHINE SELECTION PROCESS

This study uses machine-site interaction relative to machine costs as the selection criterion. Obviously, the final decision rests on a multitude of considerations, some of which are outside the equations developed. However, the utility of this study involves answering fundamental questions regarding suitability and financial viability, which must be considered prior to or in conjunction with the other factors now to be discussed.

Environmental Issues

While costs and efficiency are important criteria for machine selection, other factors within current social thinking may be just as critical. One such factor involves the environmental impact of forest logging practices on aesthetics, (Smith, 1979), soil erosion and compaction (Froehlich, 1978; Brown, Kerruish and Talsma, 1978), nutrient availability, and ecological stability (Brown, 1970). An important consideration behind the selection of the FMC 210CA log skidder was the reduced environmental impact during harvesting. Logging practices have also changed to include post logging site restoration, careful selection of winter logging areas, maximum utilization, corded landings and general awareness of logging impacts. This naturally implies additional costs and benefits to be included in final machine evaluation and selection.

Population--Type and Movement

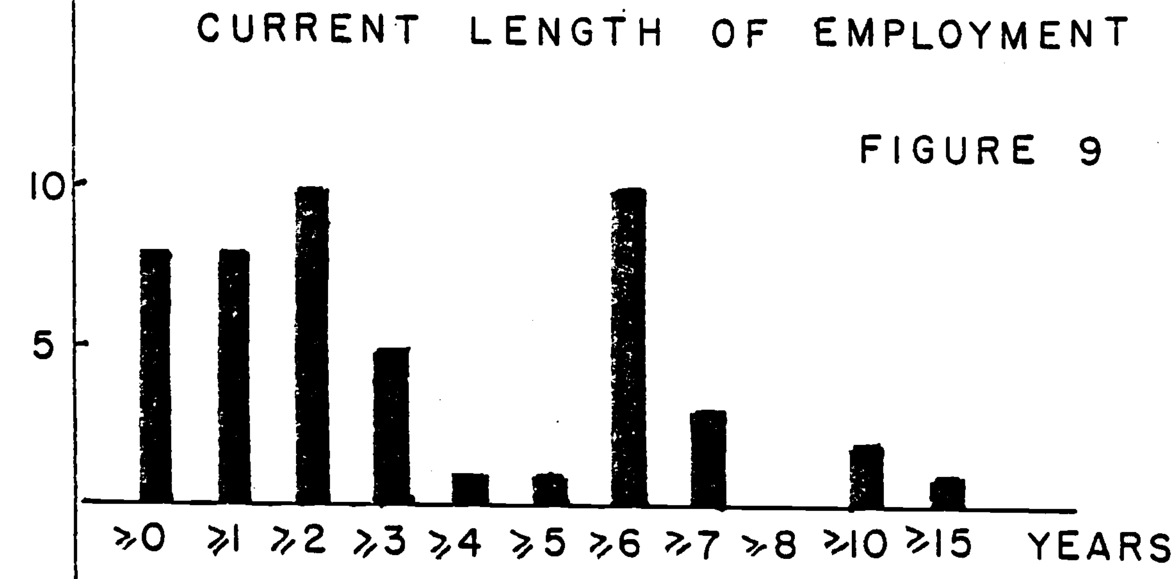
The State can best be described as rural, having 5.9 people per square kilometer, or 2.9% of the national population. Of the state's population (407,400), 75% live in the four major centers, with 40% in the capital city, Hobart. Over the last few years, migration has shown a net annual deficit of 2.05% with a population growth of 0.7%. The migration deficit probably reflects the movement of younger age groups. Considering the second largest industry in the state is timber based, the movement and content of the population is important with respect to both available and future labor pool, plus the quality of such a force. This, in turn, will affect the quality, method and stability of wood procurement systems.

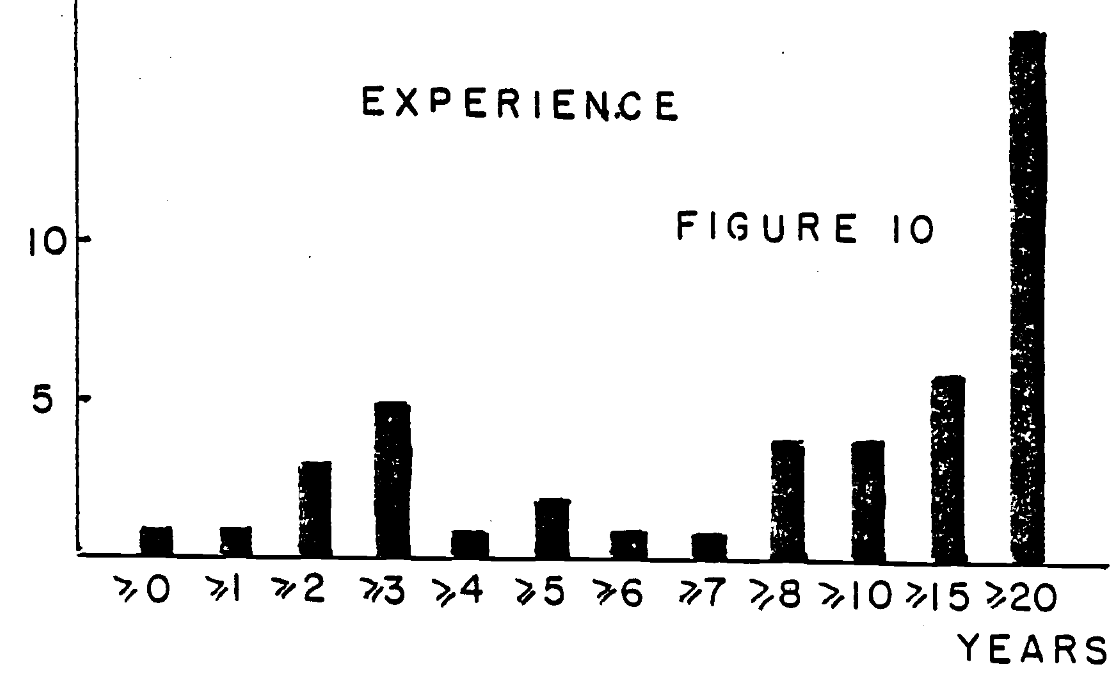
The current structure and trends within the contractor labor pool also warrant investigation with respect to maintenance of stable and efficient logging systems. For example, Figures 8-13 show the age distribution, term of current employment and level of experience in the faller and machine operator classes. Within the former the average age is 36.4 years, a majority have a large amount of experience. There appears to be no substantial new entry into this field of work, and turnover (as indicated by the length of employment with regard to level of experience) appears quite high (measured at eight percent per annum). For machine operators the average age is 31.9 years, current average length of employment is 4.8 years, with a relatively even introduction of new operators each year. Level of experience also exhibits a relatively uniform distribution. It would appear that if current trends continue the availability of trained fallers will decline, while machine operators will remain relatively constant.

Stability and availability of the labor pool has implications for the maintenance of good quality field operations and hence production,

FALLERS


AGE DISTRIBUTION
NO. FALLERS
FIGURE 8
10
5
16
21
31
41
51
YEARS


CURRENT LENGTH OF EMPLOYMENT
FIGURE 9
10
5
≥0 ≥1 ≥2 ≥3 ≥4 ≥5 ≥6 ≥7 ≥8 ≥10 ≥15
YEARS


EXPERIENCE
FIGURE 10
10
5
≥0 ≥1 ≥2 ≥3 ≥4 ≥5 ≥6 ≥7 ≥8 ≥10 ≥15 ≥20
YEARS

MACHINE OPERATORS

AGE DISTRIBUTION

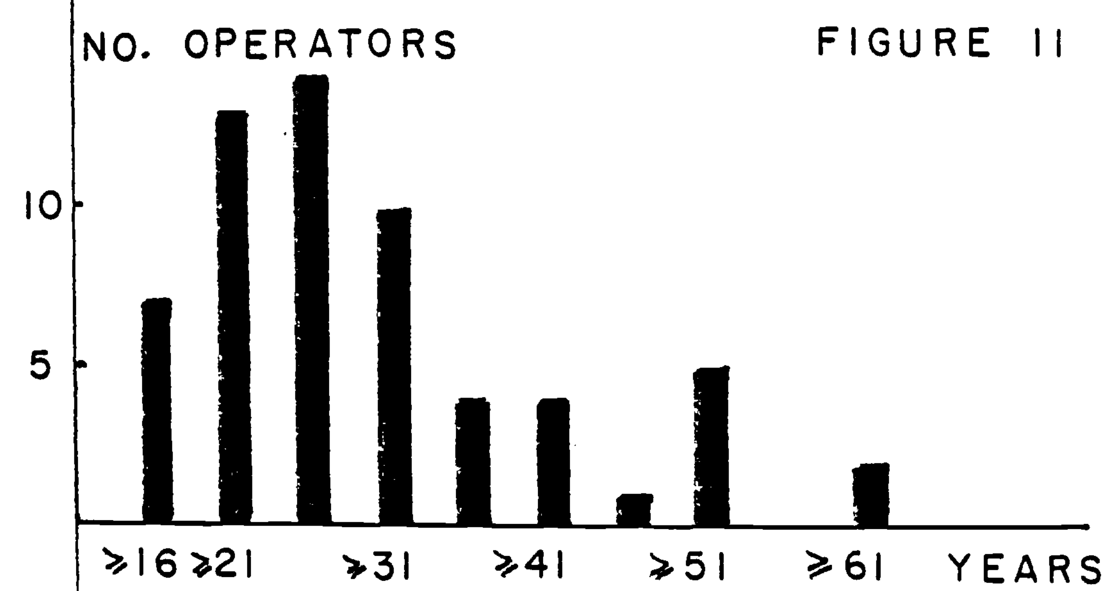


FIGURE 11

CURRENT LENGTH OF EMPLOYMENT

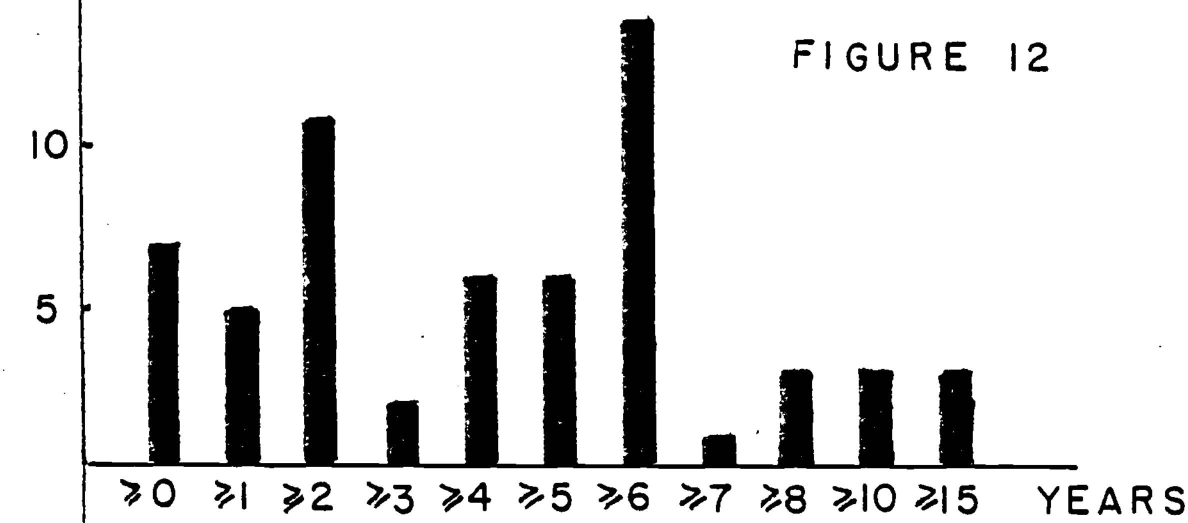


FIGURE 12

EXPERIENCE

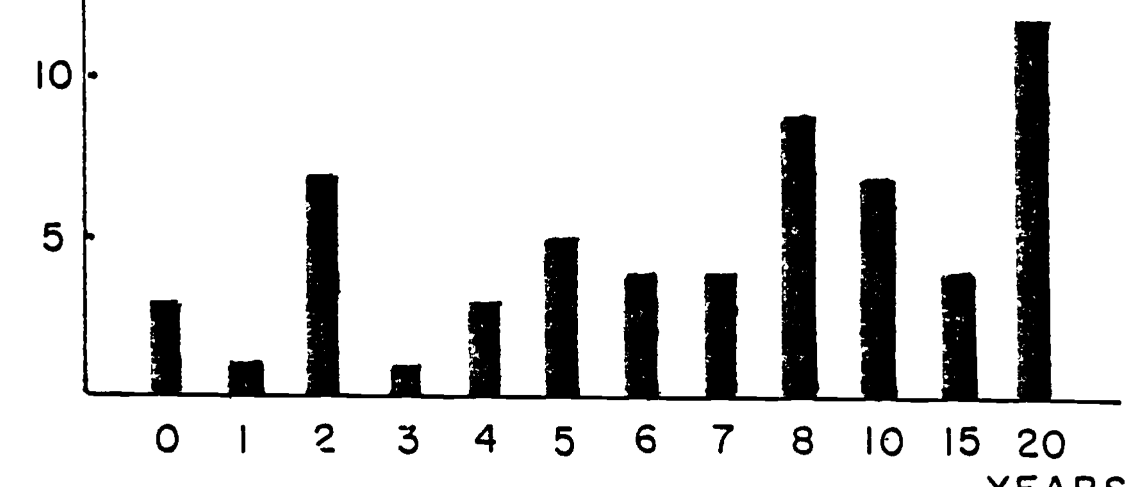


FIGURE 13

machine utility and availability. Instability will cause crew disruption, idle machinery and increased readjustment periods with a resultant decline in production. Logging machinery is becoming more exacting in the technical requirements of the operator, and as such, the successful introduction of new machinery can be much dependent on the quality and experience of the local operator. Hence, operator ability can be a significant factor in machine selection and subsequent acceptance of new machine types and logging systems.

Taxation

A fundamental influence on present machine pool (quality and quantity) has been the introduction of income tax credit on purchase of new capital equipment. Figure 3 shows the influence of its inception after 1975.

Industry Growth

Minor fluctuations have occurred in the demand for woodchips since 1972. An upturn in demand coincided with the tax credit intoduction, so the influence of demand on machine pool (quality and type) is concealed. However, as regards individual contractors, there is no doubt that expanding quotas has resulted in equipment purchases or at least upgrading.

Production Quotas

Production requirements will affect the scale and profit potential of logging operations. However, prior to discussion of these it is important to define logging potential with reference to this study. Logging potential is defined here as a function of site logging factors and is equivalent in quantitative terms to production per hour. Hence for one machine, logging potential will vary as site and logging factors change and will be reflected in changing production per hour. Similar results may be expected for other machine types, except that equivalent site and logging factors will not necessarily produce the same logging potential for all machine types.

Quota levels have a significant influence on production costs (and hence machine selection) and machine-site interaction. Figure 14 shows the general relationship between cost per unit production and unit production per hour. This relationship is the result of the fixed and variable cost components of a single machine working a full average annual hourly contribution (Appendix I), i.e., not restricted by a production quota. Assuming this full annual hourly contribution, the relationship may be written as:

$$\text{cost/unit production} = \frac{\text{(fixed cost/hour)+(variable cost/hour)}}{\text{unit production/hour}}$$

where

$$\text{fixed cost/hour} = \frac{\text{annual fixed cost}}{\text{hours per annum}}$$

The relationship is then of the form $y = \frac{a}{x}$ where

y = cost per unit production

x = production per hour

a = a constant equal to the sum of fixed and variable hourly costs

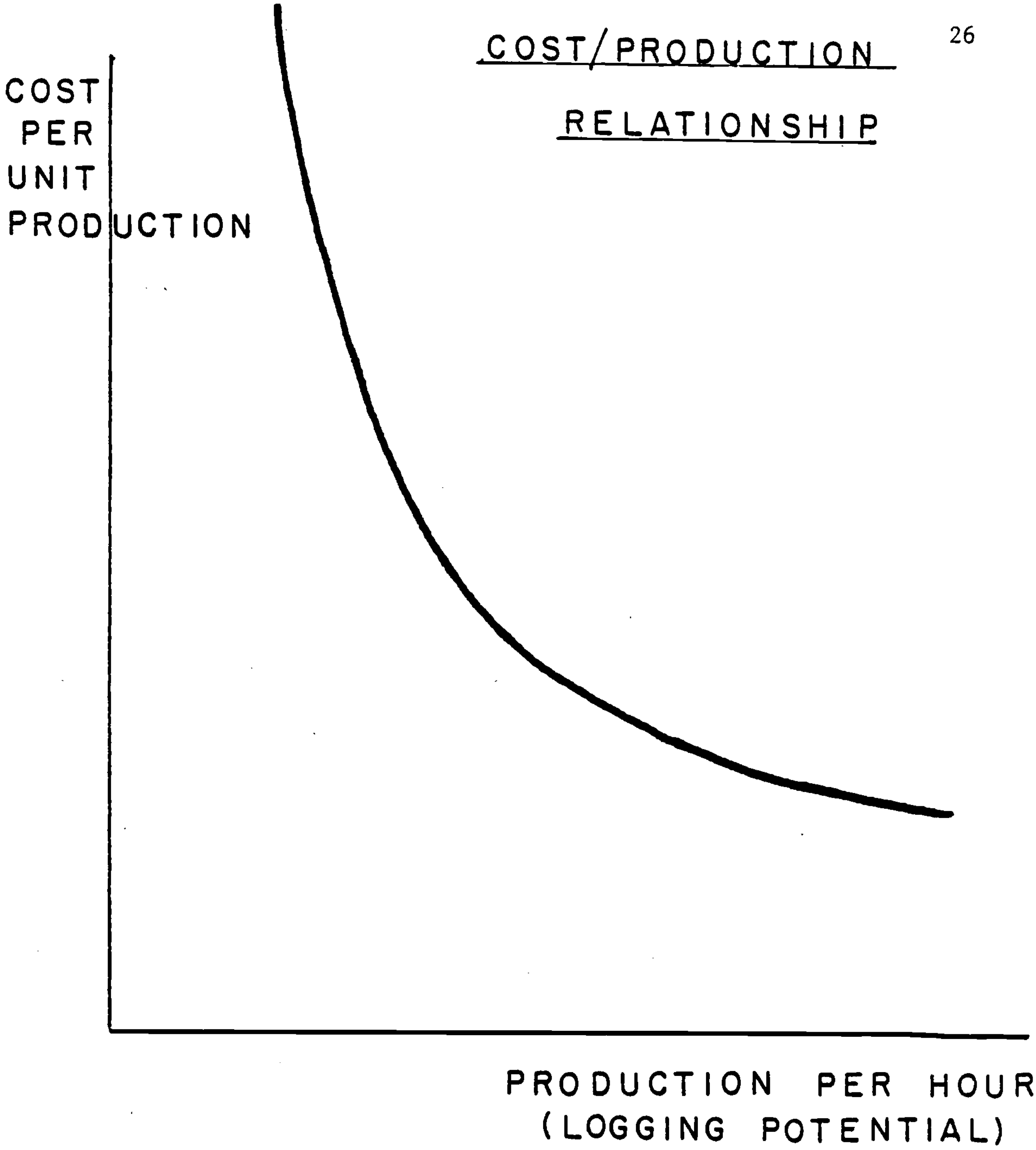

COST/PRODUCTION
RELATIONSHIP
COST
PER
UNIT
PRODUCTION
PRODUCTION PER HOUR
(LOGGING POTENTIAL)

FIGURE 14

Under quota restrictions (Figure 15), the same logic applies except that two relationships result. To the left of point A in Figure 15, logging potential (production/hour) is so low that unless hours beyond the average annual hourly contribution are worked the production quota is unattainable. To the right of point A in Figure 15 the relationship changes when quotas are imposed. The relationship differs from the first because as the logging potential improves less working hours are required to meet production requirements. Hence fixed costs/hour increase due to the increased idle time. However, with improved logging potential the unit production per hour also increases. Hence the new relationship can be written:

$$\underset{\text{(restricted)}}{\text{cost/unit production}} = \frac{\text{adjusted fixed cost/hour+variable cost/hour}}{\text{unit production/hour}}$$

where

$$\text{adjusted fixed cost/hour} = \frac{\text{annual fixed cost}}{\text{adjusted annual hourly contribution}}$$

and

$$\text{adjusted annual hourly contribution} = \frac{\text{quota production per annum}}{\text{production per hour}}$$

In the revised equation the rise in fixed cost/hour (numerator) is balanced by an increase in unit production per hour (denominator). This gives rise to the relatively uniform total cost per unit production with changing site potential as shown to the right of point A in Figure 15. Also note the influence of quota level on the cost per unit produced in Figure 15. Implications of this are discussed fully in the Results and Discussion section.

It should be noted that this influence of quota on production costs will apply to any logging operation supplying mills of limited intake

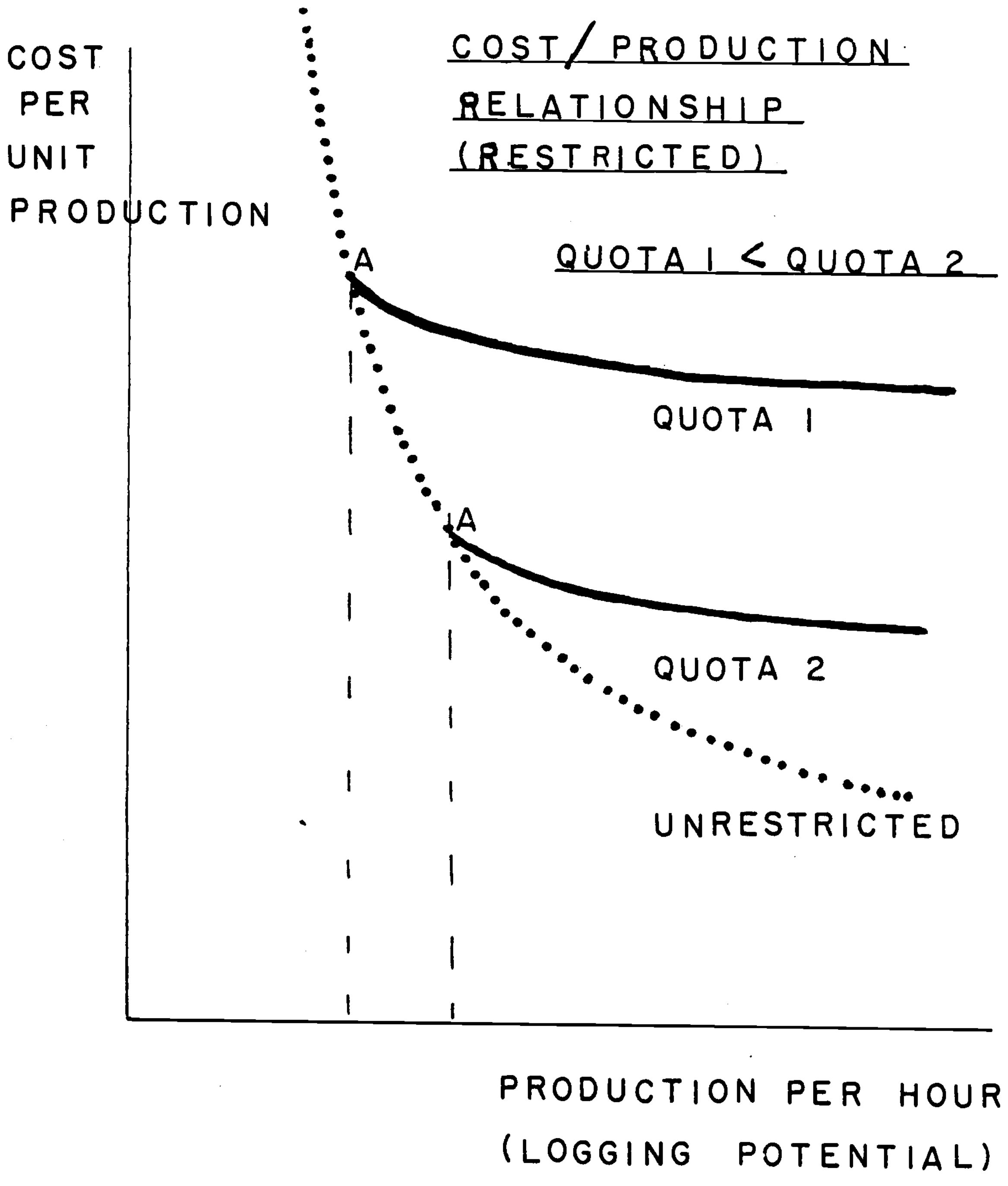

COST/PRODUCTION
RELATIONSHIP
(RESTRICTED)
QUOTA 1 < QUOTA 2
COST
PER
UNIT
PRODUCTION
A
A
QUOTA 1
QUOTA 2
UNRESTRICTED
PRODUCTION PER HOUR
(LOGGING POTENTIAL)

FIGURE 15

or under contract.

The salient features with respect to this one machine model are:

1. The imposed quota level has a significant influence on cost per unit production and hence the operation profit potential. This question of viability will affect the machine selection policy.
2. The interaction of quota level and logging potential with regard to operation feasibility and cost of production will affect machine selection.
3. As quotas increase, the logging potential must improve, so expanding quotas to achieve economies of scale, a common objective, may in fact, limit the sites suitable for such an operation, or if those sites are not available, require the purchase of additional machinery, largely eliminating any advantage of economies of scale.
4. Arbitrarily set quotas (i.e., without regard for site conditions) have a large bearing on cost per unit produced.

Figure 15 indicates that site potential should be a fundamental criterion for quota allocation along with the previously mentioned contractor potential, machine capability and timber availability. In addition, payment should be closely tied to those factors found affecting the machine productivity.

Other Selection Criteria

These may be both objective and subjective in nature. For example, past experience with certain size machinery, expected availability and/or performance, service satisfaction, machine durability, expected largest logs encountered, current financial status and current economic conditions, etc.

METHOD

Studies of this nature (Bradshaw, 1979; Dykstra, 1975, 1976; Keller, 1980; Kramer, 1978; Ohmstede, 1977; Neilson, 1978) normally aim to predict production per unit time or total cycle time. The total work cycle is commonly delineated into elements, the time duration of which are also predicted using independent variables.

Studies are of two types:

1. Production studies; long term, general studies, gathering daily summary information.
2. Time studies; detailed, short term, gathering information concerning each cycle and elements within the cycle. Delays are also categorized in detail. This type of study is naturally useful in locating problem elements of machine operation and the influence of individual factors on cycle times and elements. Studies can be continuous or on a sampling basis.

Operator and Machine Variability

An important influence on the validity of such studies is the ability and consistency of machine operators. Generally, the selected operator is assumed to be well-acquainted with the machine. This may lead to biased results with regard to machine performance. Measuring a large population of operators would alleviate this problem. However, studies of this broad nature are probably not practical with regard to time and expense.

For comparative studies the choice becomes one of using a single operator over the range of machinery and/or sites or using a number of operators each accustomed to the machine type and/or site condition.

The former assumes that the operator's ability remains constant over the range of machinery and/or sites, the latter assumes similar ability between operators.

The value of these logging studies as predictive equations is lessened if the question of operator influence is not addressed. To alleviate this inconsistency, some form of standardised operator assessment should be incorporated into logging studies for later adjustment of production or time data if required.

This particular problem is a little more complex in this study, as either an operator, or machine type, or both could result in above or below standard production levels. That is, for this study, operators did not change between machines. The problem of operator variability is addressed first.

There appears to be no universal method of performance rating, nor is there another component of time study procedure that can create so much controversy and criticism. The main problem is the individual variation in inherent knowledge, flexibility, physical dexterity, training, motivation, stability, and stage of learning. The degree of variation in performance between individuals using tree shears has been measured at an approximate ratio of 1:1.67 (Cottell et al., 1976). The question becomes one of evaluating the performance compared to a standard and then quantifying this information. Therefore, time and motion study researchers are normally interested in observing the average operator, or at least having some measure of the operators' ability against a standard.

Ole-Meiludie, Manikam and Wilson (unpublished) have proposed such an operator rating scheme relating to skidder operators. The technique basically involves measuring four criteria of an operator's ability; production, continuity, technique and safety. These are weighted for importance and job difficulty, for a final performance rating. The production criterion is measured in terms of the percentage deviation from the expected or standard production with respect to machine type and site potential. Continuity implies continuous production that includes both machine availability (likely operator-caused downtime, e.g., punctured radiators, dislodged air filters, etc.) and unnecessary delays. Technique, for this type of operator, is probably best measured using the break-out or bunching function. This function provides approximately 12 percent of the total average work cycle, but more importantly, requires far greater skill, coordination and machine knowledge than the other work elements. The average duration of this element may vary depending on site factors such as stem density, log size, topography, etc., so it is suggested that variation within this element be used as a measure of technique. The last, safety, is included to allow for the critical nature of crew disruption and lost time due to injury. Both past safety records (percentage of lost time) and the number of unsafe acts can be recorded and used to measure this criterion. Where necessary (safety, machine availability), the industry or company averages are used as standards.

No safety or continuity information was available during this study; however, both the technique and production criteria have been used here to evaluate the performance of each operator.

The operator adjustment system first required a comparative criterion to establish a standard operator. In this case operator technique was selected (Table 2).

Having determined a standard operator, and because those actual field results were to be used for comparative purposes with results from the predictive equations, all standard operator time study data was excluded from equation formulation. Having noted the relevant site conditions for the standard operator and subsequent actual production per hour, this value was adjusted for all different sites according to the predictive equations developed in this study. That is, adjusted for slope yarding distance and volume per hectare, assuming that the number of logs per turn, volume per log and volume per cycle remained constant as per the on-site operator. This adjusted production was considered the standard production per hour for that site and used for comparison with actual production obtained by the on-site operator.

One operator differed significantly (95% confidence level) from the calculated standard, which confirmed earlier suspicions from the field. Table 2 shows this operator had the lowest rating for technique. In addition, inspection of the residual errors for the production predictive equation indicated that for this particular operator the residual errors were consistently negative. That is, the combined production data pertaining to this operator virtually behaved as an outlier for the whole equation.

Table 2. Standard deviation of bunching time (minutes)/# logs/turn for each operator studied.

Operator	Standard deviation bunching/# logs/cycle time
1	0.6571 minutes
2	0.2846
3	0.6411
4	0.3687
5	0.6068
6[z]	1.0880
7	0.8573
8	0.4702
9	0.9625
10	0.5700
11	0.2750
12*	0.4847
13*	0.6048

Mean = 0.6053

Average operator = #13 = standard

*Excluded from model formulation

[z]Operator found significantly ($\alpha = .05$) below standard.

As regards the contractor machine pool and its treatment in this study, the log skidders were divided according to horsepower (SAE, net engine flywheel horsepower). Two sections were delineated; 90-150 and greater than 150. To limit any individual machine differences or peculiarities due to machine history, age, etc, the study concentrated on those better quality machines within the machine pool. The machine types, sizes and hours are listed in Table 3. The ages of the machines studied ranged from one to five years and the hours from 300-5000.

Machines were observed to their considered limit of safe operation.

The machine producing less than standard production, i.e. operated by operator #6, is #11, which has well below average total machine hours for the machine pool studied.

The adjustment factor proposed in this study, before becoming completely definitive with regard to causal nature (operator, machine or operator and machine), requires further detailed analysis of machine capability at the time of study. However, the results of the study do indicate that some adjustment is appropriate at this stage, and until further explicit data is available can be regarded as an operator/machine adjustment.

Machine Work Elements

The nature of the model determined that the method of data collection involve detailed time study of the machine types undergoing their work cycles. The machine elements were divided and hence defined as:

1. Outhaul. The time taken between the machine leaving the landing (a fixed center point) and arriving at the log site.

Table 3. Model type, SAE hp, machine hours and purchase status of all the study machines.

Brand	#	Model	SAE HP	Machine hours (Sept. 1979)	Purchased
John Deere	1	540B	90	1600	New
	2	540B	90	2000	New
	3	640B	110	300	New
International Franklin	4	S9	138	5000	New
	5	170	112	2400	New
	6	*170	112	5000	New
	7	180	130	3600	New
Clarke	8	667	112	2000	New
	9	*667	112	3600	Second-hand
	10	668	164	1700	Second-hand
	11	[z]668	164	1400	New
Caterpillar	12	518	120	500	New
	13	528	175	2800	New

*Excluded from model formulation

[z]Operator/machine found significantly below standard (95% confidence level)

The latter is defined by a change of gear, marked decrease in machine speed or lowering of the blade to indicate that unbroken ground has been entered.

2. Bunching logs. The time taken between entering the log site and positioning the logs ready for hooking. The element is complete when the operator leaves the cabin.

3. Hooking. The time taken between the operator leaving the cabin and the load readied in position for inhaul. The completion of this element is similarly defined by operator action e.g. selecting forward gear.

4. Inhaul. Defined as the time taken between leaving the log site and stopping on the landing in preparation for unhooking.

5. Unhooking. The time taken between the operator stopping the machine on the landing and returning to the machine in position to move away from the landing.

6. Operating delay. Recorded during any element and classified as communication, log stacking, repairs and maintenance, refueling, landing changes, log trimming, and rehooking. These delays are considered as expected events outside the work element and requirements of daily operation.

7. Non-operating delay. Recorded during any element and classified as congestion and unnecessary delays (e.g. delays through operator error or poor technique). These delays are considered as unnecessary and inefficient components of daily operation. Lunch breaks were included in this section but differentiated later in production results.

Independent Variables

The time studies were conducted over as wide a range of sites as possible. Emphasis was placed on site variability as study duration was limited. The elements were recorded to the nearest 0.1 minutes by two field assistants using two-way radios to maintain contact during restricted visibility. One recorder was responsible for recording all machine elements, the other (on the landing) recorded log dimension data, plus other machine and truck loading and arrival information (this study was part of a broader logging system analysis).

As the study was conducted during normal contractor field operations, the delineation of specific experimental areas was not possible. Instead, the study used each new skid trail as an experimental area and data regarding distance, slope, ground conditions, volume per hectare, etc., were recorded for each trail. By selecting a range of contractors a broad spectrum of site conditions could be studied (even within one logging block) with no disruption to normal logging practices.

The site conditions and logging factors are presented in Table 4, and analysis indicates that the best predictive equations are thus:

cycle time = fn(SYD, Vol./turn, # logs/turn, Vol./ha, ACCESS or Dry Soil)

production/hour = fn(SYD, Vol./turn, # logs/turn, Vol./ha, ACCESS)

The Study

Data was collected from May 29, 1979 to August 29, 1979 (winter, spring). Thirteen contractor operations were selected, based on machine type, likely sites encountered and a trained skidder operator.

Table 4. Explanatory variables used in this study.

Variable (units)	Abbr.	Expected sign: Cycle time	Expected sign: Production	Definition
Slope Yarding Distance (m) (±10m)	SYD	+	-	The distance from the landing fixed point, to the log hooking point, for each cycle
Skid trail Slope (%)	STS	±	±	(Figure 16) The average weighted skid trail slope resulting from clinometer readings every 50 m, for each turn
Absolute STS (%)	ASTS	+	-	As above except absolute values used.
Volume per turn (cu. m) (girth and length to nearest cm)	Vol/turn	+	+	Gross volume from girth (OB) and length measurement. (Tasmanian Forestry Commission Volume Tables)
Average volume per log per turn (cu.m)	Vol/log/turn	+	+	The quotient of volume per turn and # logs per turn
Number logs per turn	# logs/turn	+	-	A count of the number of logs per turn

(cont'd)

Table 4. (cont'd)

Variable (units)	Abbr.	Expected Cycle time	Expected Production	Definition
Logging slope (%)	LS	+	-	Figure 16. The average log slope recorded at the log site, for the trial.
Stems per hectare	Stems/ha	-	+	Derived from an estimate of area logged and stump count for each trial, i.e., the merchantable number of stems per hectare
Volume per hectare (cu. m/ha)	Vol/ha	-	+	Derived from an estimate of the area logged and the volume hauled, i.e., gross merchantable volume (4" top end diameter over bark)*
Ground conditions (qualitative)	GC I-IV	+	-	Table 5. A measure of rockiness obtained from 3, 10x10 m plots located at 0, 1/3 and 2/3 SYD.
Ground conditions (quantitative)	GC	+	-	The actual percentage of rockiness, average rock diameter and their product from the above plots.

*This volume would be that returned from forest inventory. The occurrence of defect is extremely variable even within logging blocks and the magnitude is generally not apparent until harvesting.

(cont'd)

Table 4. (cont'd)

Variable (units)	Abbr.	Expected Cycle time	Expected Production	Definition
Soil condition (qualitative) (wet/dry)	Dry soil	+	-	Soil wetness/dryness. Wet conditions described by an obvious and repeated loss of traction plus high soil plasticity
Access (Qualitative) (good/bad)	ACCESS (=good access)	+	-	Machine accessability to the log site. Bad access described by extensive undergrowth and/or prohibitive quantities of residues from past sawlog operations.
Soil type (qualitative) Mathinna Dolerate Granite	Soil	+	-	Three basic soil types
Operators/machines		-	+	Each operator and machine was identifiable to allow comparison.

COMPARISON OF SKID TRAIL SLOPE AND LOGGING SLOPE

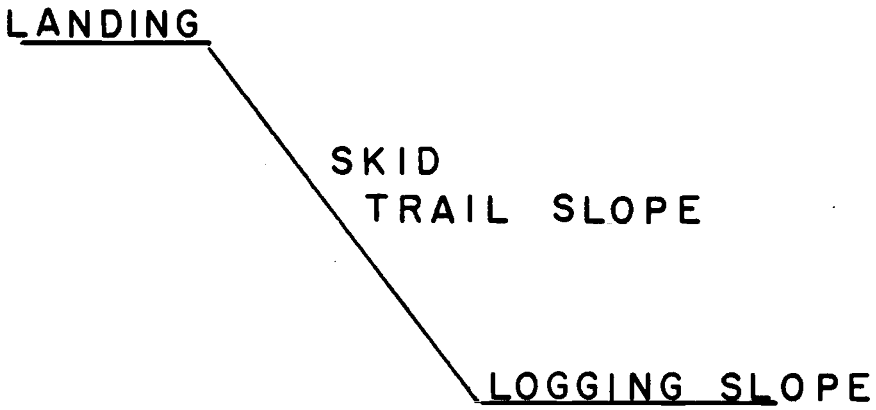


FIGURE 16

Table 5. Ground conditions classification*.

% cover	Rock diameter (m) >2m	1-2m	$\frac{1}{2}$-1m	$<\frac{1}{2}$m	0
100	GCV	GCV	GCV	GCV	GCI
75	GCV	GCV	GCV	GCIV	GCI
50	GCIV	GCIV	GCIV	GCIII	GCI
25	GCIV	GCIV	GCIII	GCII	GCI
0	GCI	GCI	GCI	GCI	GCI

*Based on a fixed frame crawler machine (an integral part of most operations studied)

GCI: No obstruction to the passage of such a machine

II: Minor hindrance

III: Some re-routing necessary to obtain logs; machine progress visibly reduced

IV: Very difficult for machine passage; only limited areas available where the machine can work.

V: Mechanically and economically impossible working conditions for a fixed frame machine

The study did not concentrate on one machine type as to do so with regard to the diversity of machine types would have severely limited the general application of the equation. Instead it was considered more appropriate to classify the machines into horsepower groups and produce predictive equations for these groups and hence the contractor pool.

The field data collection consisted of moving with the operation as it changed landing and skid trails. Termination of measurement at any one particular site was mainly a function of the limited time available for the study and the large number of possible site conditions expected. Observations for the low horsepower skidder group totalled 206, while 259 cycles were recorded for the large horsepower skidder group.

THE ANALYSIS

A thorough investigation of the independent variables was conducted using the correlation coefficients between all variables, and stepwise and backstep procedures. The correlation coefficients were used to develop likely equations and also explain formulations using the stepwise and backstep methods.

Variable selection criteria (see Table 8) was based on a combination of adjusted R^2 values, t values, percentage change in R^2 and MSE values, and a measure of the total squared error or bias indicator, Cp (Neter and Wasserman, 1974).

Once acceptable R^2 values were obtained more emphasis was placed on the Cp factor and t values to at least provide an unbiased predictive equation with significant (95% confidence level) independent variables. For the equations presented, the addition of the last independent variable caused a percentage increase in adjusted R^2 values of 0.47 to 2.60% and MSE values of 0.73 to 4.60%.

A review of current literature (Bradshaw, 1979; Dykstra, 1975, 1976; Keller, 1980; Kramer, 1978; Neilson, 1978, Ohmstede, 1977) indicates:

1. The common use of the least squares method for descriptive and predictive curve fitting in logging studies.
2. The large variety of independent variables used and found significant by different authors.
3. The low R^2 values, typical of many logging studies.
4. The particular difficulty in predicting certain elements of the machine work cycle, e.g. hooking, unhooking, and bunching time.
5. The common simple linear equation form.

The analysis undertaken here (i.e. equation formulation) is guided by a logical sequence of tests to determine the validity of the proposed least squares equation.

The data was first divided and analysed according to the following:

1. Low horsepower machines: cycle time and production per hour equations.
2. High horsepower machines: cycle time and production per hour equations.
3. Both machine types combined: cycle time and production per hour equations.

In addition to these, some consideration of operator/machine variability and operating delays plus a cost analysis is provided. The final result is a series of predictive equations and a cost/unit production-site interaction analysis. The equations have also been validated using additional data independent of the formulation process.

The analytical technique employed was the least squares method (Draper and Smith, 1966; Neter and Wasserman, 1974; Pindyck and Rubinfeld, 1976). The implicit assumptions behind this technique include (Hann, unpublished); for unbiased least squares estimators of the equation parameters.

1. The equation is linear in its parameters and the error term is additive (linearity).
2. The number of sample observations is greater than the number of parameters to be estimated (degrees of freedom).
3. All independent variables are non-stochastic variables and measured without error (deterministic).

4. No perfect multicollinearity exists between independent variables.

5. The expected value of the error term is zero (over/underspecification).

Meeting the next two assumptions provide best linear unbiased estimators.

6. Variance about the model is homogenous (heteroskedasticity).

7. The random errors are uncorrelated (autocorrelation).

Meeting the last two allows the application of exact tests, development of exact confidence levels, and least squares estimates of the model parameters to be uniformly minimum-variance unbiased estimators.

8. The random errors are normally distributed (normality).

9. The form and number of independent variables in the population model is known before parameter estimation.

The tests mentioned previously involve critical assessment of the equations against these assumptions during formulation. The tests involve (in order), normality, linearity, specification, autocorrelation, heteroskedasticity and multicollinearity.

1. Normality (assumption 8). The linearity, specification and a number of autocorrelation and heteroskedasticity tests are dependent upon normality of the residual errors. Additional difficulties in not meeting this assumption have already been outlined.

   The two classical statistics for the examination of normality are $b_1^{\frac{1}{2}}$ (skewness) and b_2 (kurtosis), (Pearson and

Please, 1975; Bowman and Shenton, 1975) where

$$b_1 = m_3^2/m_2^3$$

$$b_2 = m_t/m_2^2$$

$$m_r = \sum_{i=1}^{n} (y_i-\bar{y})^r$$

If the random variables are normally distributed then

$$E(b_1^{\frac{1}{2}}) = 0 = B_1^{\frac{1}{2}}$$

$$E(b_2) = 3 = B_2$$

and the degree of variation from these values determines the degree and direction of the skewness or kurtosis. For example, a statistic b_2 of greater than three indicates a leptokurtic distribution and conversely less than three indicates a platykurtic distribution. Bowman and Shenton (1975) have proposed a joint test for $b_1^{\frac{1}{2}}$ and b_2 presenting exclusion contours of the test statistics (90%, 95%, 99% confidence levels) for sample sizes ranging from 20 to 1000, based on the robustness of four standard tests (the one sample t-test, the two sample t-test, the chi-square test and the F-test).

In this study

Low HP	Production/hour equation		
		$b_1^{\frac{1}{2}}$	0.3433
		b_2	3.1402
	Cycle time equation		
		$b_1^{\frac{1}{2}}$	0.1022
		b_2	2.7000

High HP	Production/hour equation	
	$b_1^{\frac{1}{2}}$	0.0476
	b_2	2.4571
	Cycle time equation	
	$b_1^{\frac{1}{2}}$	0.4308
	b_2	2.9844
Total HP	Production/hour equation	
	$b_1^{\frac{1}{2}}$	0.0286
	b_2	2.9167
	Cycle time equation	
	$b_1^{\frac{1}{2}}$	0.0587
	b_2	2.7892

The tests indicate that all equations exhibit normality of residual errors at the 95% confidence level.

2. Linearity (assumption 1). Obviously a basic assumption to be met before linear regression techniques are applicable. No one comprehensive test is available; however, a variety of checks, such as inspection of independent variable and residual plots are possible.

In the case of the production per hour equations (Figure 17) obvious non-linearity existed in all independent variable plots. The shape of the divergence indicated a logarithmic transformation may be appropriate. This was further confirmed by the diverging nature of the residual plots (Figure 18)

PRODUCTION PER HOUR — SYD (LOW HP)

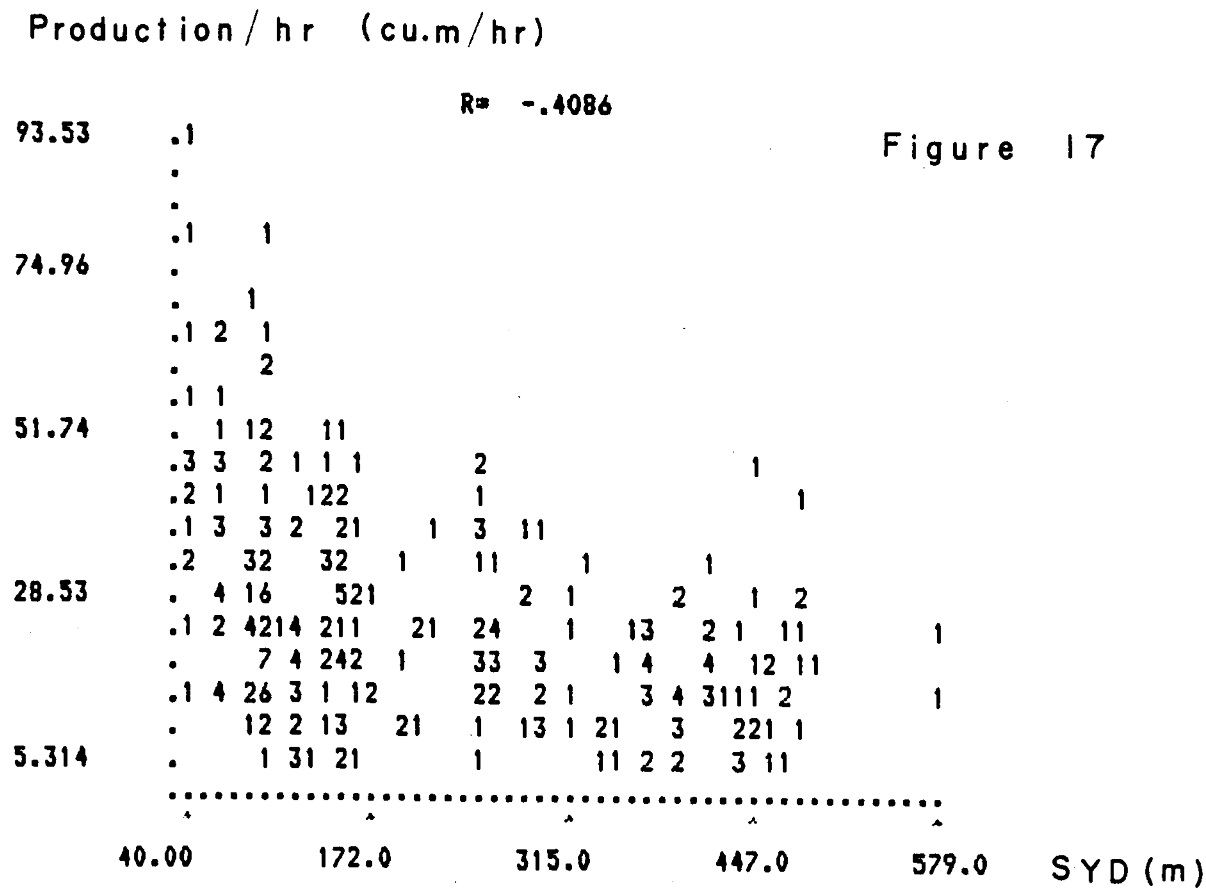


Figure 17

PRODUCTION EQUATION (LOW HP)

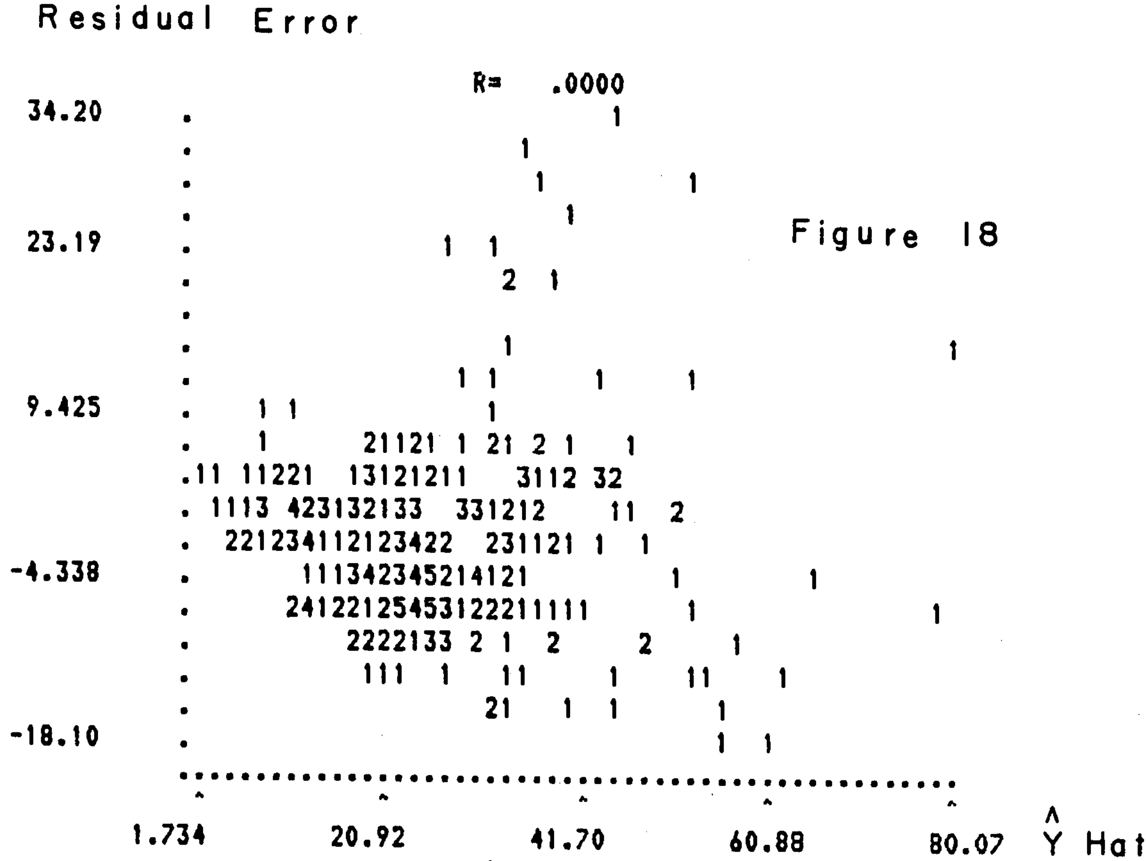


Figure 18

indicating a multiplicative error term or heteroskedasticity (see heteroskedasticity). Baskerville (1972) suggests in this case the model of form:

$$Y_i = (BX_i^{\alpha})\varepsilon_i$$

which can be transformed with logarithms to

$$LN(Y_i) = LN(B) + \alpha LN(X_i) + LN(\varepsilon_i)$$

subsequent transformation resulted in independent variable and model residual plots such as Figures 19 and 20.

With regard to the cycle time equations no obvious deviation from linearity was apparent in the independent variable plots, with the exception of the total HP equation. For the low HP and high HP equations log transformation did little to improve the respective predictive ability (as indicated by the R^2 value).

3. Specification (assumption 5). This can result from relevant variables not being recognized or measured, appropriate transformations not being used and/or poor technique, and poor data sets distorting the influence of variables and hence affecting rejection/acceptance tests. Following from (2) the residual plots can be checked to ascertain appropriate transformations. Similarly, data from outside the study can be used to test the equation. In this case two such trials (from both horsepower groups) were used to calculate actual production and cycle time. These results were then compared to that predicted by the cycle time and production per hour equations. The results are given in Appendix II and indicate

Ln PRODUCTION PER HOUR – SYD (LOW HP)

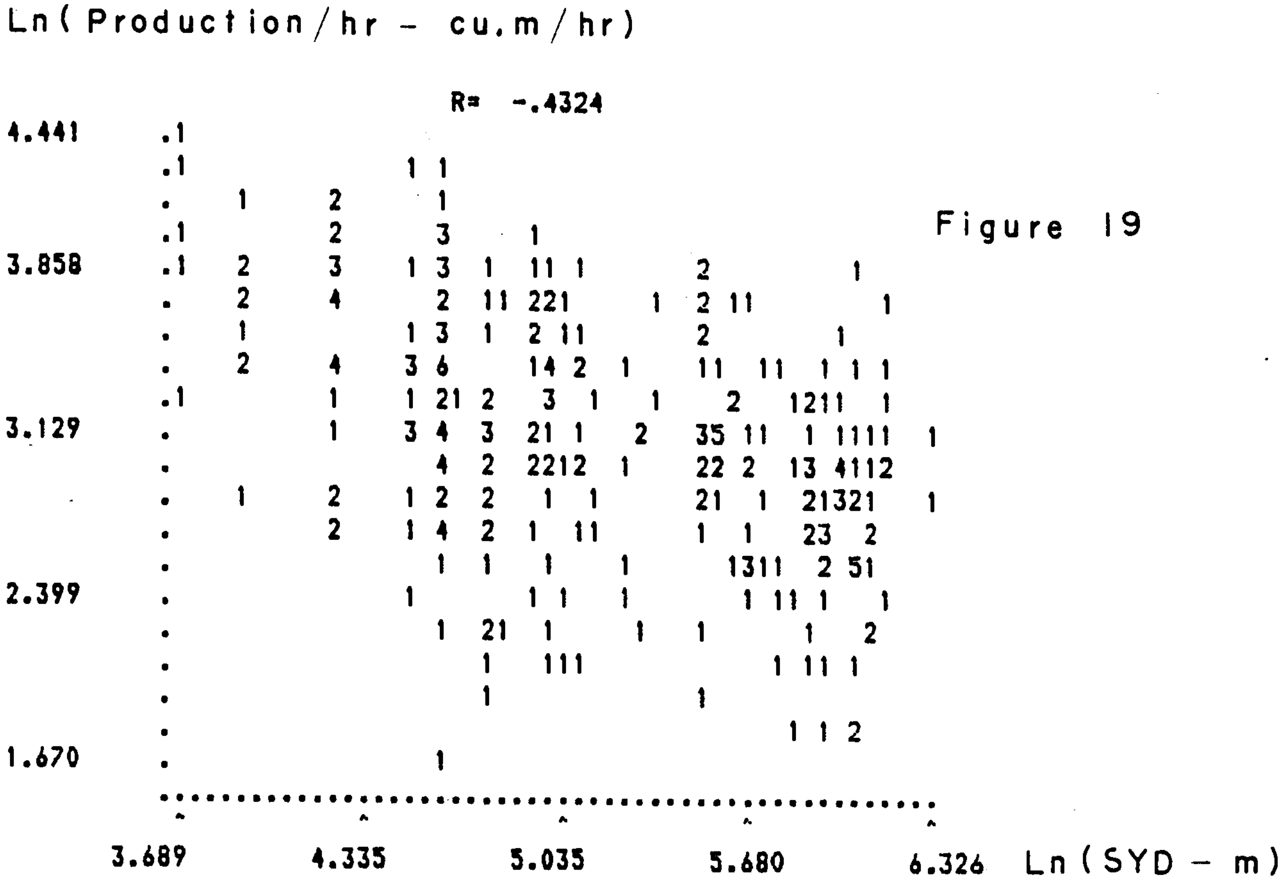


Figure 19

Ln PRODUCTION EQUATION (LOW HP)

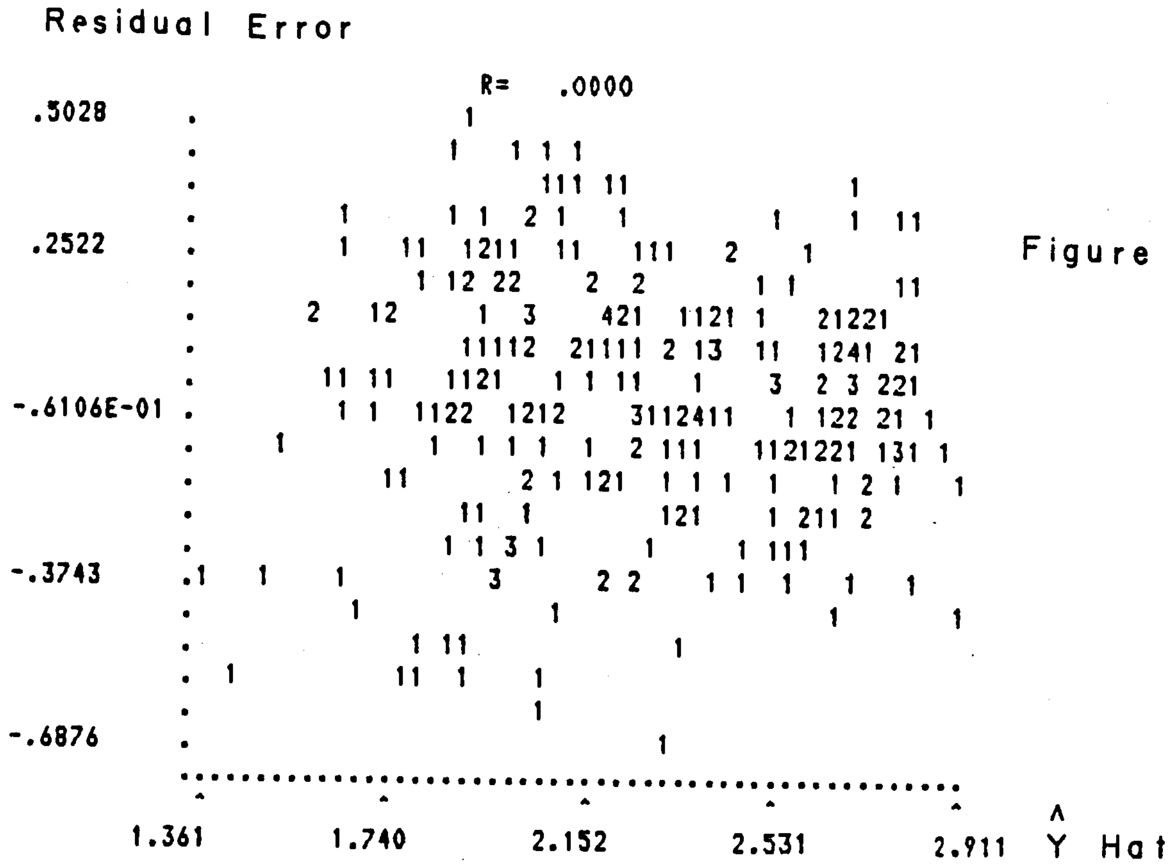


Figure 20

that at a 95% confidence level no significant difference was recorded between actual and predicted values.

4. Autocorrelation (assumption 7). This phenomenon occurs when the random error terms are correlated, i.e. dependent random variables, and hence may be prevalent in studies requiring repetitive measurements e.g. permanent plot records, and in this case, the repetitive nature of the machine cycles. In particular, field observation indicates that possible autocorrelation may exist due to skid trail deterioration or compaction on each machine pass. Although this is most likely at the commencement of skid trail use. Compaction trials on dry soils (Wilson, Kerruish and Moore, 1980) indicate that repeated machine passage does little to alter compaction once initial impact is recorded. The same pattern may occur on wet, muddy trails once initial impact is completed resulting in a reasonably constant loss of traction. These possible events required that each trial in this study be checked for autocorrelation. This was accomplished using the Durbin-Watson test (Durbin and Watson, 1950, 1951) followed by the Geary test (Geary, 1970) if the former proved inconclusive.

The Durbin-Watson test uses the test statistic

$$D = \sum_{i=z_2}^{n} \frac{(e_i - e_{i-1})^2}{\Sigma_{i=1}^{n} (e_i)^2}$$

where e_i = sample residual, which assumes first order serial correlation including normality of residual errors. The Geary test uses the count of the number of sign changes that occur amongst the residuals, implying that few sign changes infers serial correlation. The probability of fewer sign changes occurring is given by

$$T = \sum_{x=0}^{s} \frac{(n-1)!}{x!\,(n-x-1)\,!} \Big/ (2^{n-1}-1)$$

where x = # sign changes

n = # observations

The test statistic T if $\leqslant \alpha$ (desired testing level) implies the hypothesis of no serial correlation is rejected. In no case was autocorrelation significant. This may be due to the fact that the wet soil trials were already established at the time of measurement i.e. significant loss of traction was already occurring. For the dry soil trials, the number of machine passes had no significant effect on machine cycle time or production per hour.

For all the equations, autocorrelation was tested by ordering all data in field trial chronological order. No autocorrelation was found using the Geary test.

5. Heteroskedasticity (assumption 6). This phenomenon occurs when the distribution of error terms is not constant over all observations, and is inherent in situations when the response follows a distribution in which the variance is functionally related to the mean. Failure to meet this assumption causes the variances of the parameter estimates to be biased. This naturally negates all standard testing and confidence interval construction procedures when using the ordinary least

squares technique.

The Spearman rank correlation test was used on all equations to establish the nature of the relationship between the absolute value of the residuals and the independent variables and predicted variable. The results for the latter are shown in Table 6. The test indicates that heteroskedasticity does not exist within the proposed equations. Note, however, that improper log transformation of a linear equation (cycle time-low horsepower) produces a negative heteroskedasticity.

6. <u>Multicollinearity (assumption 4)</u>. In cases of high multicollinearity the parameter estimates using ordinary least squares regression coefficients may change erratically when new independent variables are added to the equation. In these types of predictive equations, multicollinearity can cause error in future predictions unless the relationships in the collinear data remain the same. Problems may also arise in the selection of variables when unnecessary rejection may occur based on low t values brought about by inflated variances of the coefficient.

Each equation was tested for collinearity by inspecting the correlation between each variable in the model. No perfect collinearity was apparent. However, a few interesting cases of higher than expected collinearity were evident, and appeared to reflect the style of logging operation conducted. Examples are discussed below drawn from the low HP equations.

Table 6. Heteroskedasticity. Spearman Rank Correlation Test (α=.05).

Predicted value vs. absolute residual value

	Normal model	LN transformed
Cycle time model		
Low HP	NS	** negative
High HP	NS	NS
Total HP	** positive	NS
Production/hour model		
Low HP	** positive	NS
High HP	** positive	NS
Total HP	**positive	NS

1. Cycle time equation

	# logs/cycle
Slope Yarding Distance	.414
Stems/ha	.369

2. Production per hour equation

	# logs/cycle
Slope Yarding Distance	.546
Stems/ha	.579

Both equations indicate that the logging operator may adjust the load depending on the distance to be hauled, i.e., the longer the distance the more logs hauled. Similarly, stands of more stems per hectare resulted in the operators tending to bring in more logs.

Other variables apparently affected by an adjusted style of operation are skid trail slope and logging slope. That is, steeper slopes tended to be associated with high production trials. The reason being the high correlation between SYD and these slope variables, such that as slope increased the SYD decreased providing a compensating factor against steep slopes. The declining SYD under these conditions reflects the change in technique (e.g. increased landing density) and management practice (more intensive roading) to combat adverse grades. This adjustment for slope is further addressed in the Results and Discussion section.

7. Other assumptions. Those concerning degrees of freedom, deterministic variables and the form and number of variables

have all been met in the data collection process.

The conclusion is that the proposed equation parameters are uniformly minimum-variance unbiased estimators, and the application of exact statistical tests and development of exact confidence intervals are valid.

RESULTS AND DISCUSSION

Before presenting the proposed equations it is important to note the description (mean, range, etc.) of each independent variable and element used in this study. Figure 21 gives the relevant histograms and Table 7 gives the ranges within each variable over which the equations are applicable. As will be noted, the ranges are broad, making the equations readily applicable in almost all field situations.

Equation Presentation

The predictive equations for all horsepower groups are presented in Table 8, together with relevant statistical indicators of predictive power, variable significance and equation bias. The equations presented in italics are logarithmic equations. All equations are unbiased as indicated by the Cp factor (Neter and Wasserman, 1974), and particularly for the production per hour equations demonstrate an unusually high R^2 value. For all equations, all but two variables are significant at the 95% confidence level. The remaining two are significant at the 90% confidence level.

Of the variables not selected: volume/log/turn was eliminated due to high collinearity with volume/turn and # logs/turn and instead volume/turn and # logs/turn selected due to their high predictive value and low collinearity. The ground condition parameters were found not significant for this type of machinery, which may be expected considering the nature of the machines. Similarly soil type was found to be not significant and probably very extensive studies would be required to reveal any differences.

INDEPENDENT VARIABLE HISTOGRAMS

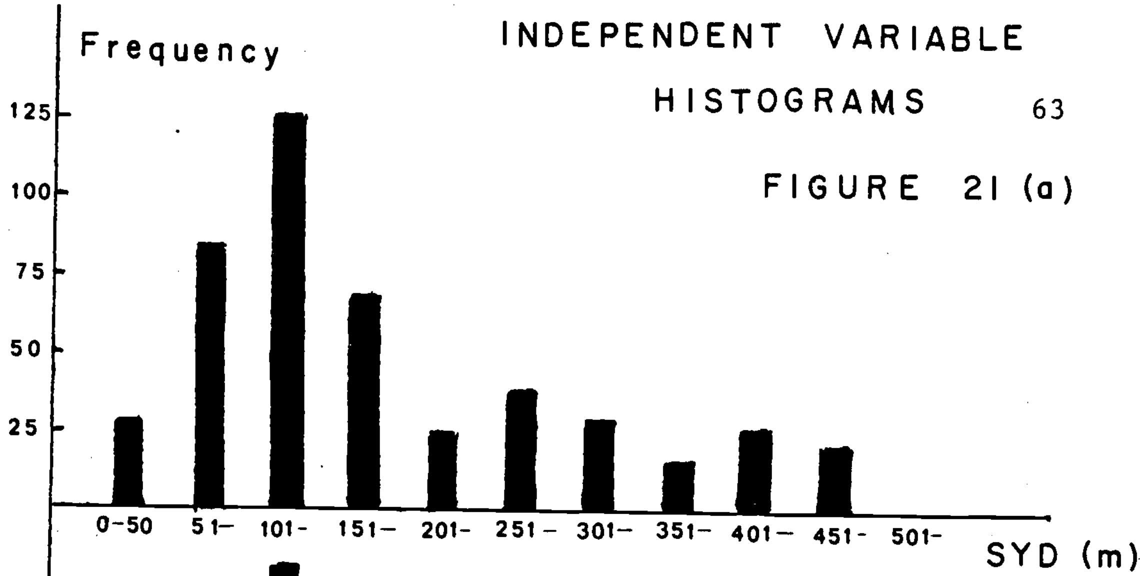
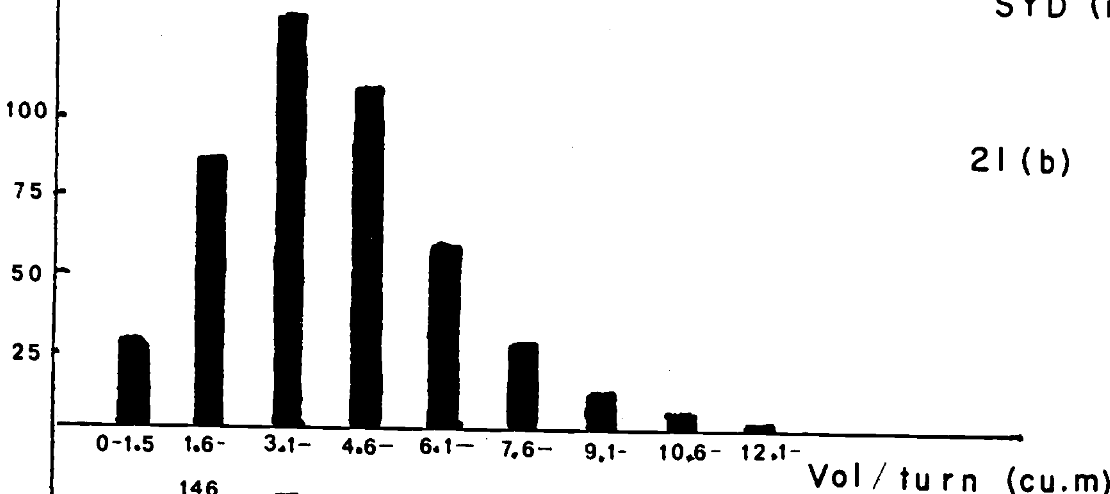
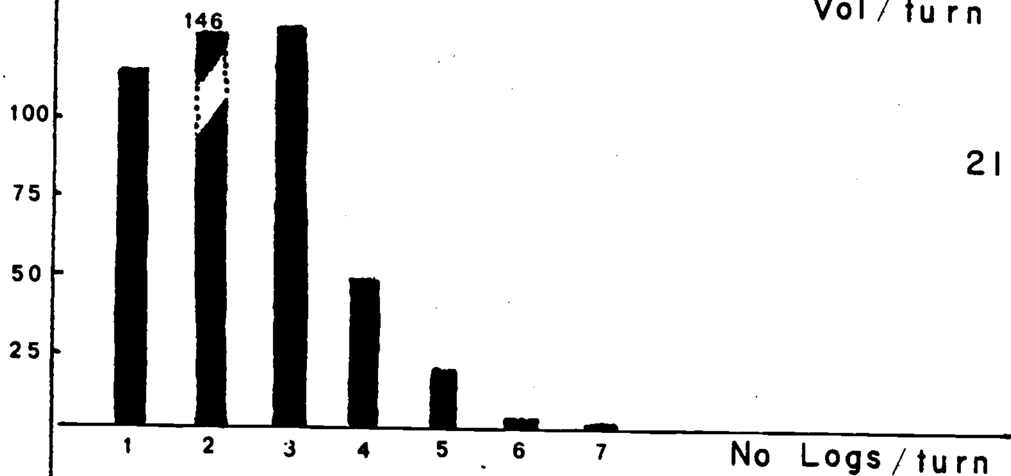


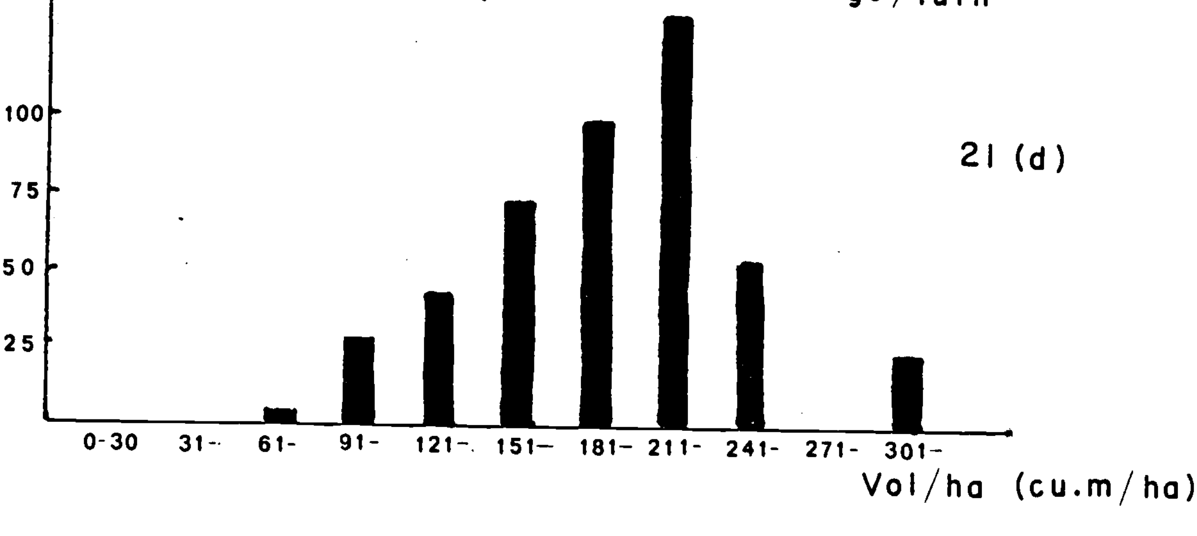
FIGURE 21 (a)



21 (b)



21 (c)



21 (d)

Table 7. Minimum, maximum, mean and standard deviation of the independent variables and work elements.

	90-150 HP				>150 HP			
	Min.	Max.	Mean	St. dev.	Min.	Max.	Mean	St. dev.
T.O.(min)	0.30	5.80	2.18	1.13	0.20	5.50	1.61	0.99
B.O.(min)	0.00	6.80	1.40	0.94	0.00	9.90	2.15	2.01
Hook(min)	0.30	9.30	3.31	1.81	0.40	13.30	2.53	1.91
T.I.(min)	0.30	8.70	2.73	1.52	0.50	9.90	2.57	1.65
Unhook(min)	0.30	3.00	0.94	0.46	0.30	3.70	0.76	0.48
TOTAL(min)	2.50	21.30	10.56	3.91	2.30	24.20	9.59	4.53
# OBS.		206				259		
SYD(m)	40.00	500.00	224.32	136.05	20.00	460.00	148.84	103.25
Slope (%)	-20.00	21.00	1.18	11.53	- 35.00	11.00	- 1.90	9.31
Vol/turn(M^3)	0.62	12.93	4.50	2.32	0.67	11.16	4.64	2.18
# logs/turn	1.00	5.00	2.30	1.10	1.00	7.00	2.50	1.21
Vol/log/turn(M^3)	0.43	11.29	2.39	1.71	0.34	9.53	2.38	1.93
Log slope(%)	5.00	25.00	16.26	7.35	5.00	35.00	6.54	5.20
Stems/ha	51.00	156.00	92.98	33.82	50.00	200.00	109.98	35.69
Vol/ha(M^3/ha)	85.50	233.0	184.12	37.50	103.5	365.0	215.39	54.20
% rock cover	0.00	30.00	11.94	12.80	0.00	65.00	7.82	17.94
Rock cover x size	0.00	15.00	6.11	6.48	0.00	46.00	5.99	13.88
Gr. Cond. I ;	104		observations		195		observations	
II ;	56		"		28		"	
III ;	46		"		0		"	
IV ;	0		"		36		"	
V ;	0		"		0		"	
Dry soil ;	178		"		192		"	
Wet soil ;	28		"		67		"	
Good access ;	165		"		249		"	
Bad access ;	41		"		10		"	
Dolerite soil;	167		"		68		"	
Granite soil ;	15		"		191		"	
Mathinna soil;	24		"		0		"	

Table 8. Predictive equations and relevant statistical indicators.

	Intercep	Vol/turn (cu. m)	SYD (m)	# logs/turn	Vol/ha (cu. m/ha)
Low HP class					
Cycle time (minutes)	7.2985 (7.709)	0.3269 (4.870)	0.0160 (12.878)	1.1202 (7.413)	-0.0183 (-4.408)
Production/hr (cu. m/hr)	*3.0817 (6.932)*	*0.8432 (26.165)*	*-0.3751 (-12.984)*	*-0.2113 (-5.937)*	*0.1897 2.536*
High HP class					
Cycle time (minutes)	5,4382 (4.002)	0.3008 (3.978)	0.0277 (14.402)	0.8377 (5.966)	-0.0060 (-1.695)
Production/hr (cu. m/hr)	*2.5348 (5.472)*	*0.8634 (26.606)*	*-0.3687 (-12.462)*	*-0.2182 (-5.898)*	*0.2528 (3.612)*
Total HP class					
Cycle time (minutes)	*1.2137 (3.892)*	*0.1467 (6.361)*	*0.3601 (18.148)*	*0.2344 (9.353)*	*-0.2081 (-4.155)*
Cycle time (minutes)	*0.8848 2.565)*	*0.1485 (6.430)*	*0.3641 (18.298)*	*0.2206 (8.808)*	*-0.1525 (-2.535)*
Production/hr (cu. m/hr)	*2.8806 (9.236)*	*0.8533 (36.988)*	*-0.3601 (-18.148)*	*-0.2345 (-9.353)*	*0.2081 (4.155)*
Production/hr (operator/machine adjusted) (cu. m/hr)	*2.7827 (9.193)*	*0.8623 (38.516)*	*-0.3607 (-18.732)*	*-0.2469 (-10.148)*	*0.2262 (4.654)*

( ) t value - 95% confidence level

Italics = logarithmic equations

(cont'd)

Table 8. (cont'd)

	ACCESS (1=good) (0=bad)	Dry soil (1=good) (0=bad)	Adj. R^2	MSE	CP	Residual error variance
Low HP class						
Cycle time (minutes)	-1.2389 (-3.271)		0.7419	4.3364	6.00	
Production/hr (cu. m/hr)	*0.0858 (2.055)*		*0.8403*	*0.0521*	*6.00*	*0.05081*
High HP class						
Cycle time (minutes)	-2.248 (-2.715)		0.7229	6.0947	6.00	
Production/hr (cu. m/hr)	*0.1879 (2.136)*		*0.8398*	*0.0696*	*6.00*	*0.06823*
Total HP class						
Cycle time	*-9.3865) (-2.310)*		*0.7003*	*0.0622*	*6.00*	*0.06150*
Cycle time (minutes)		*-0.0661 (-1.817)*	*0.6993*	*0.0624*	*6.00*	*0.06177*
Production/hr (cu. m/hr)	*0.0865 (2.310)*		*0.8309*	*0.0622*	*6.00*	*0.06150*
Production/hr (operator/machine adjusted)	*0.1018 (2.802)*		*0.8439*	*0.0586*	*6.00*	*0.06792*
(cu. m/hr)	*( )*	*t values - 95% confidence level*				

Italics = logarithmic equation

Of particular interest is the negative coefficient of the # logs/turn variable in the production equations, i.e. as the number of logs increases, production can be expected to decline. The main reason is this variable's correlation with individual work elements e.g.

	# logs/turn
Outhaul	0.41
Bunching time	0.18
Hooking time	0.52
Inhaul	0.32
Unhooking time	0.21

It appears that the number of logs per turn has an influence on hooking time (31% of total cycle time) and inhaul and outhaul functions. The last may seem dubious except that the # logs/turn is correlated with the SYD (0.41) which in turn is highly correlated with inhaul (0.79) and outhaul (0.78). That is, longer slope yarding distances mean higher inhaul and outhaul times, but at the same time operators tend to bring in more logs on the longer hauls.

The low correlation between bunching time and # logs/turn should also be noted implying that single logs can be just as difficult to manoeuver and align into position for hooking as a number of logs.

Further inspection of the production equations reveals that the negative coefficient of this variable is balanced by a positive coefficient for volume/turn. This implies that production per hour will be higher if all the volume is in one log rather than many, and also that there is a limit to the number of logs that should be bunched for the sake of building a load. The production equation for the total HP class (operator-machine adjusted) indicates this breakeven to be when

$$0.2469 LN (\# \text{ logs/turn}) = 0.8623 \; LN (\text{Vol./turn})$$

This relationship is presented in Figure 22. Referring to Figures 21(b) and (c) it would appear that possibly in only very few cases did the operations fail to meet the breakeven point.

Model Comparison--Appendix II

1. Cycle time and production per hour equations. The cycle time equations were used to predict production per hour using

$$\text{predicted production per hour} = \frac{60}{\text{predicted cycle time}} \times \text{average volume/turn}$$

and compared to the equivalent predicted production using the production equations (average conditions used; SYD = 182.28 m, Vol./turn = 4.58 cu. m, # logs/turn = 2.41, and Vol./ha = 201.5 cu. m/ha). For all horsepower classes no significant difference (95% confidence level) was found between the two production estimates.

2. Alternative cycle time equations. (ACCESS or soil condition). The predicted cycle time for the alternative cycle time equations (total HP class) were compared under equivalent logging conditions. No significant differences (95% confidence level) was found between estimates.

   The cycle time equation including the dry soil parameter is probably best suited to day to day prediction due to the very

VOLUME / TURN — No. LOGS / TURN

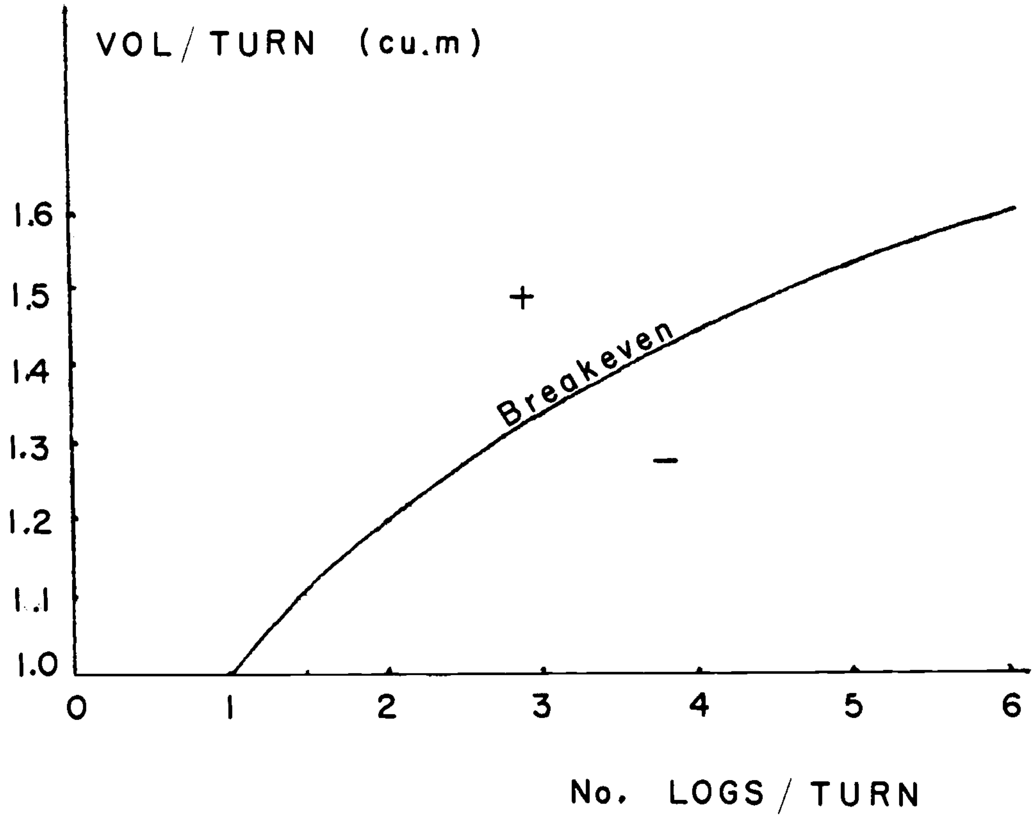


FIGURE 22

nature of the independent variables. All the other equations, while valuable on a day to day basis readily lend themselves to planning and prediction in the long term.

2. Low horsepower and high horsepower. Statistical tests (95% confidence level) found no significant difference between the two classes. That is, over the range of conditions outlined in Table 7, no production or cycle time advantage was found using the higher horsepower machine. The cost repercussions are discussed in a later section.

3. Operator/machine adjusted equation. For that trial found to be significantly below the standard expected production, the actual field data was converted to standard values, using a multiplication factor of 1.21, which represents the deviation of the actual recorded production from the standard.

   The resultant adjusted equation represents an improved adjusted R^2 value of 1.56% compared to the relevant unadjusted equation. Using average site conditions recorded in the study the difference represents an increase of 0.3 M^3/hour using the operator adjusted model. This difference is more accentuated as the volume/hectare and volume/turn increase and # logs/turn decreases, i.e., as logging conditions become more favorable.

   The improvement in the adjusted R^2 value, the decrease in MSE and decline in residual error term variance has resulted in the selection of this equation for future comparisons with actual field situations, machine selection decisions and cost analyses, etc.

Comparison with the total HP unadjusted model shows no significant difference at the 95% confidence level.

4. Operating delays. During the study period the individual operating delays ranged from 0-52 minutes, and the irregular occurrence of these has necessitated its inclusion in the equation as an average lost time spent on operating delays. An average of 15.3% was recorded as operating delays or lost production. Hence, an adjusted figure, for average working conditions might be:

$$\text{production/hour} = 27.65\ M^3/\text{hour}\ (.847)$$
$$= 23.42\ M^3/\text{hour (delay adjusted)}$$

Further analysis indicates that an additional 24.6% is lost due to non-operating delays. This includes all lunch breaks and rests (15.0%). The breakdown of daily working hours is then as follows:

75.4%	productive time (includes 15.3% operating delays)
15.0%	lunch breaks and rests
9.6%	non-operating delays

Potential productive hours = 75.4% + 9.6%
= 85%

Logarithmic Equation Adjustment

During the validation process and equation comparisons it was noted that when comparing means of a logarithmic transformed equation to an untransformed equation, a special conversion of the logarithmic equation mean and variance is required to produce arithmetic units (Baskerville, 1972). That is, conversion from logarithmic value to a representative arithmetic value is not a direct logarithmic conversion. This results from converting a normal LN(Y) distribution at a given X to a Y distribution at that X which will certainly be skewed.

Conversion is such that if the estimated mean of $LN(Y)=\hat{\mu}=\hat{\beta}+\hat{\alpha}LN(X)$ then the arithmetic estimates are given by $\hat{Y} = e^{(\hat{\mu}+\hat{\alpha}^2/2)}$ and $\hat{\alpha}^2 = e^{(2\hat{\alpha}^2 + 2\hat{\mu})} - e^{(\hat{\alpha}^2 + 2\hat{\mu})}$

Slope Adjustment

The influence of skid trail slope is of particular interest in this study. As already noted, operations tend to adjust to their respective logging conditions to provide a cushion against adverse factors or conversely take advantage of high production sites. Hence, some correlations between # logs/turn and SYD, stems/ha and # logs/turn, etc. have been observed. With regard to skid trail slope, it was noted that as slopes increased the recorded slope yarding distance tended to decrease, providing a cushioning effect against adverse slope. This relationship is a result of both deliberate management practice in road location and density, and operator self-adjustment (e.g. density and size of landings). Relevant coefficients are given below:

Low HP class	Skid trail slope
SYD	-0.4897
Vol./turn	-0.2431
# logs/turn	-0.4061

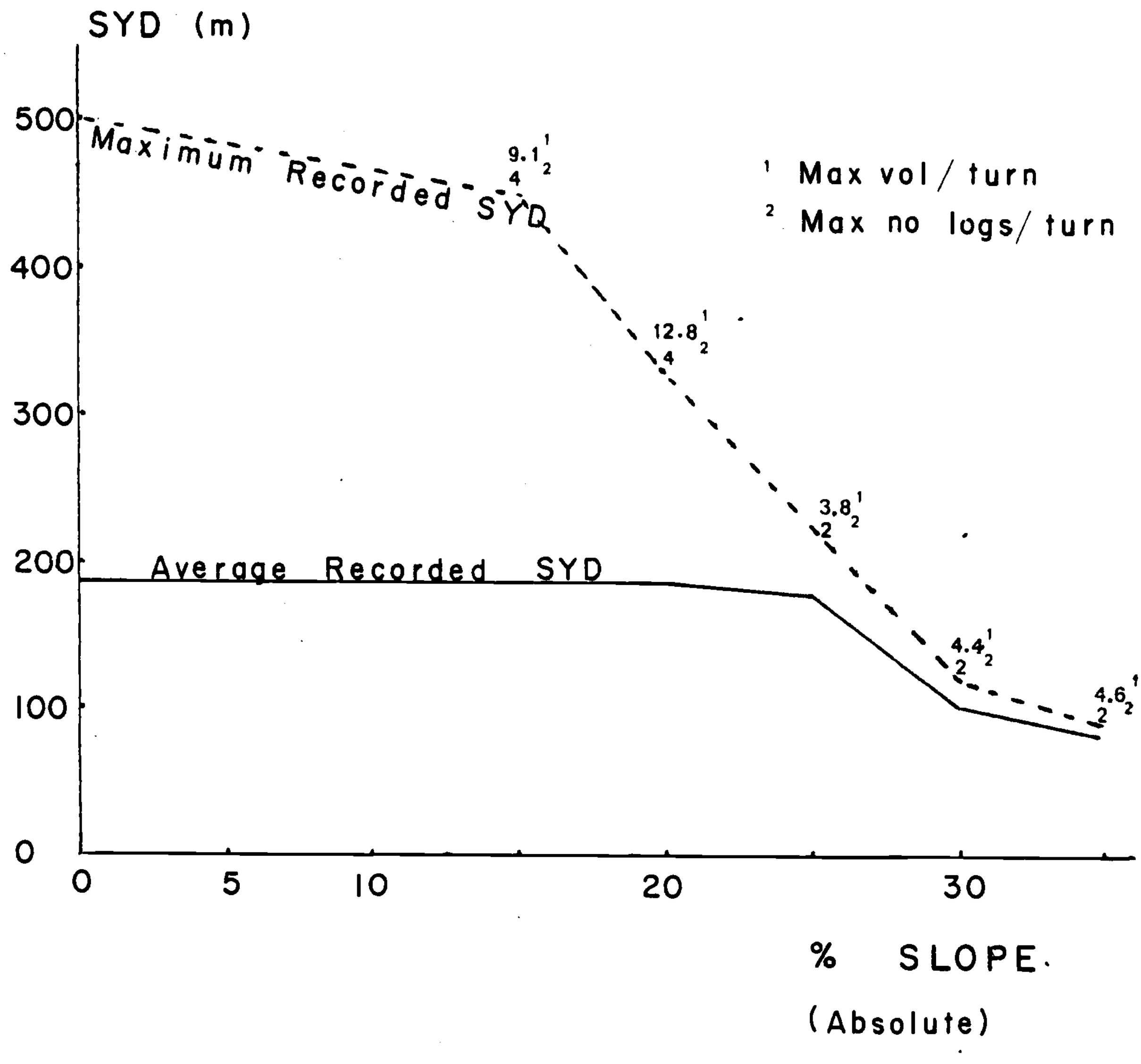
Because operations studied were conducted in such a manner, it was not possible to obtain information for long slope yarding distances at adverse grades. However, for interpretation of the predictive equations, Figure 23 shows the average and maximum slope yarding distances, recorded for given absolute skid trail slopes. A dramatic shift in preferred maximum slope yarding distance is seen beyond 15% absolute slope. Hence, the equations as formulated and presented imply that provided management, and operation technique are such that field practice remains within the limits shown by Figure 23, the influence of skid trail slope is insignificant with regard to production per hour and cycle time.

Slope yarding distance is not the only variable influenced by slope. Both # logs/turn and to a lesser extent, volume/turn, tend to decline as the skid trail slope increases. The maximum values of these variables at adverse grades are given in Figure 23 to allow interpretation of the predictive equations.

Because of these adjustments within operations for the influence of slope, the proposed equations should be interpreted in light of the current management and field practices. Hence, while slope does not actually appear in the equations as a significant variable, its influence is still exerted in the limitation of possible values taken on by variables within the equations (SYD, # logs/turn and volume/turn).

Collinearity

The collinearity between all independent variables in the total horsepower (operator-machine adjusted) equation is presented in Table 9.



THE RELATIONSHIP BETWEEN SYD AND ABSOLUTE SLOPE

FIGURE 23

The only significant feature is the collinearity between SYD and # logs/turn which has already been discussed.

Table 9. Within Model Collinearity

	Total horsepower--cycle time and production/hour				
	SYD	Vol./turn	# logs/turn	Vol./ha	ACCESS
SYD	X	0.181	0.385	-0.238	-0.025
Vol./turn		X	0.196	0.200	-0.036
# logs/turn			X	-0.184	0.116
Vol./ha				X	0.029
ACCESS					X

Model Validation

Two trials (12 & 13) were excluded from model formulation, involving both horsepower classes. All proposed models were tested against the actual field results obtained and in no case was any significant difference (95% confidence level) found between the predicted and actual production estimates. Appendix II gives the results of these comparisons.

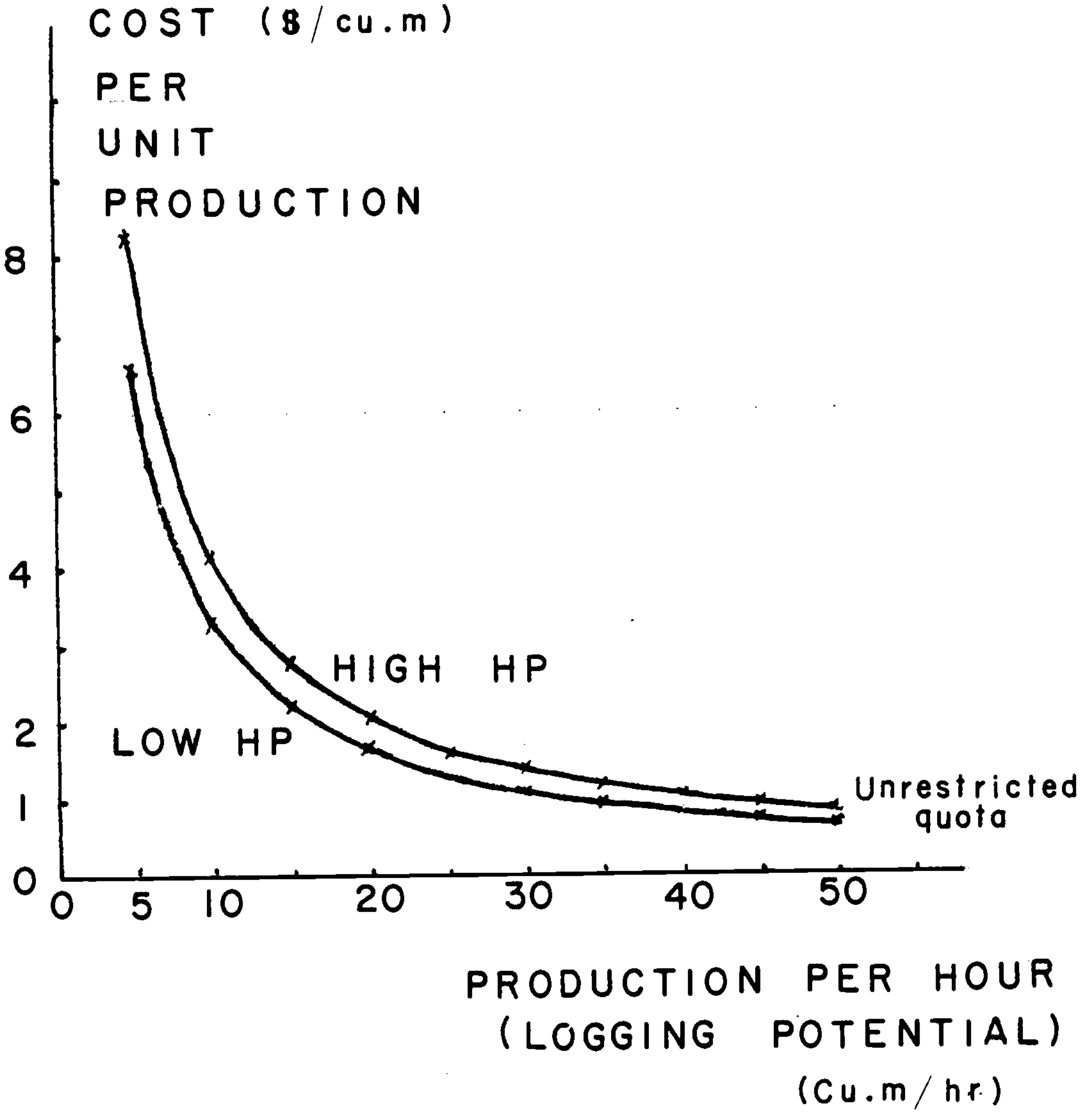
Cost Study

Machine owning and operating costs have been calculated (Appendix III) using contractor and manufacturer sources. Total costs for the two machine sizes have been estimated at $A32.80/hour and $A41.37/hour for the low and high horsepower groups, respectively. The hourly cost refers to actual working hours.

Figure 24 gives the cost curve per unit production of both machine classes. Figures 25 and 26 give the cost curves using four production quota levels of 250, 450, 650 and 850 M^3/week, for both machine classes.

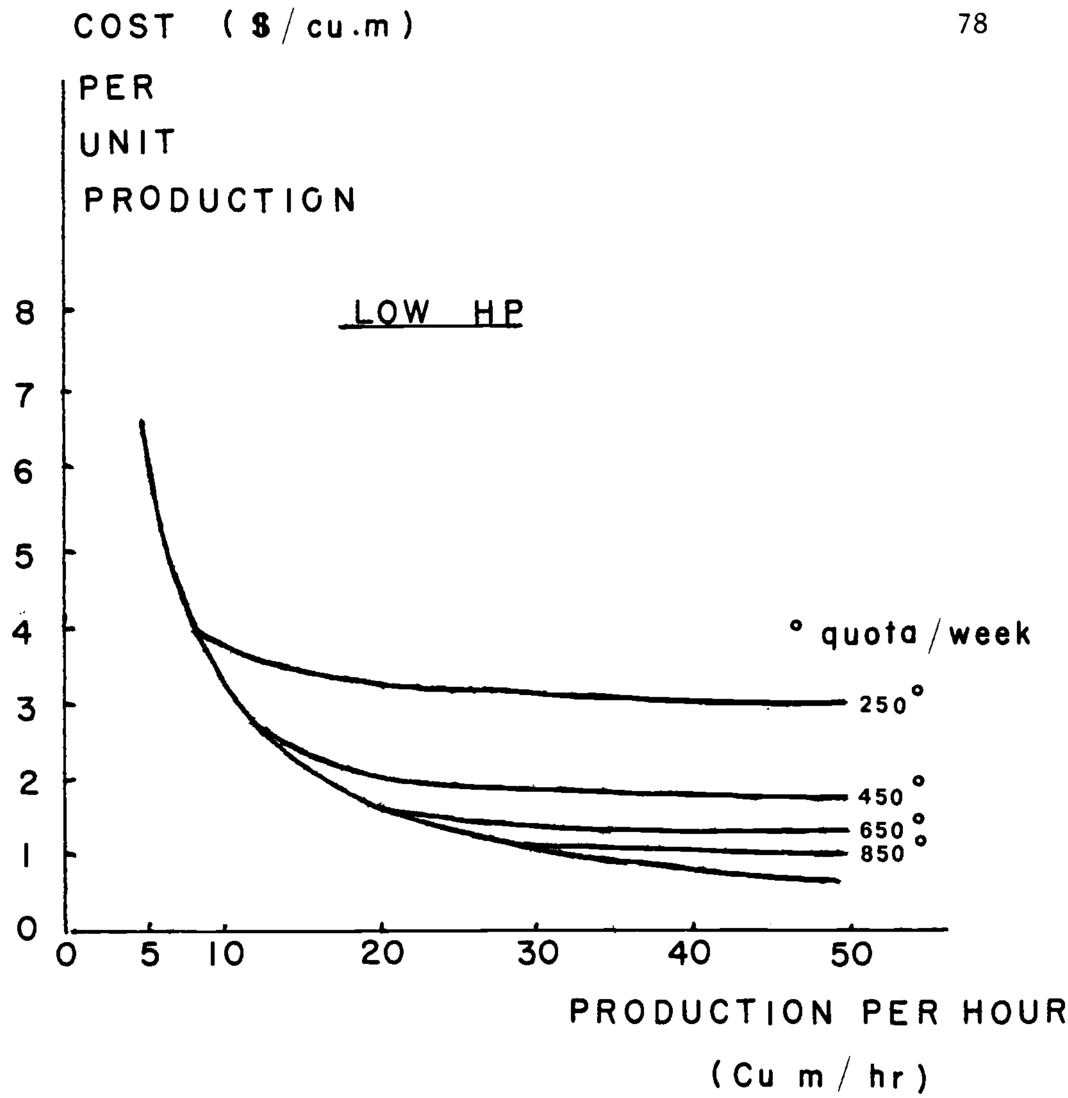
From Figure 24 it would first appear that the high HP group would require additional revenue to meet costs for similar sites, compared to the low HP group. The compensating factor is that if any technological advantage exists for the more expensive machine group, then one particular site will produce two logging potentials (production per hour), one for each machine group. If the difference in logging potential outweighs the difference in cost per unit production, then the improved technology has a cost saving advantage.

The machine cost is a function of the machine itself plus those relevant site factors e.g. affect of abrasive soils on tire wear. For this study, costs for average site conditions have been used, and further intensive examination is required to better differentiate between costs due to soil type, ground conditions and slope, etc. These costs together with logging potential (a result of studies of this type), can



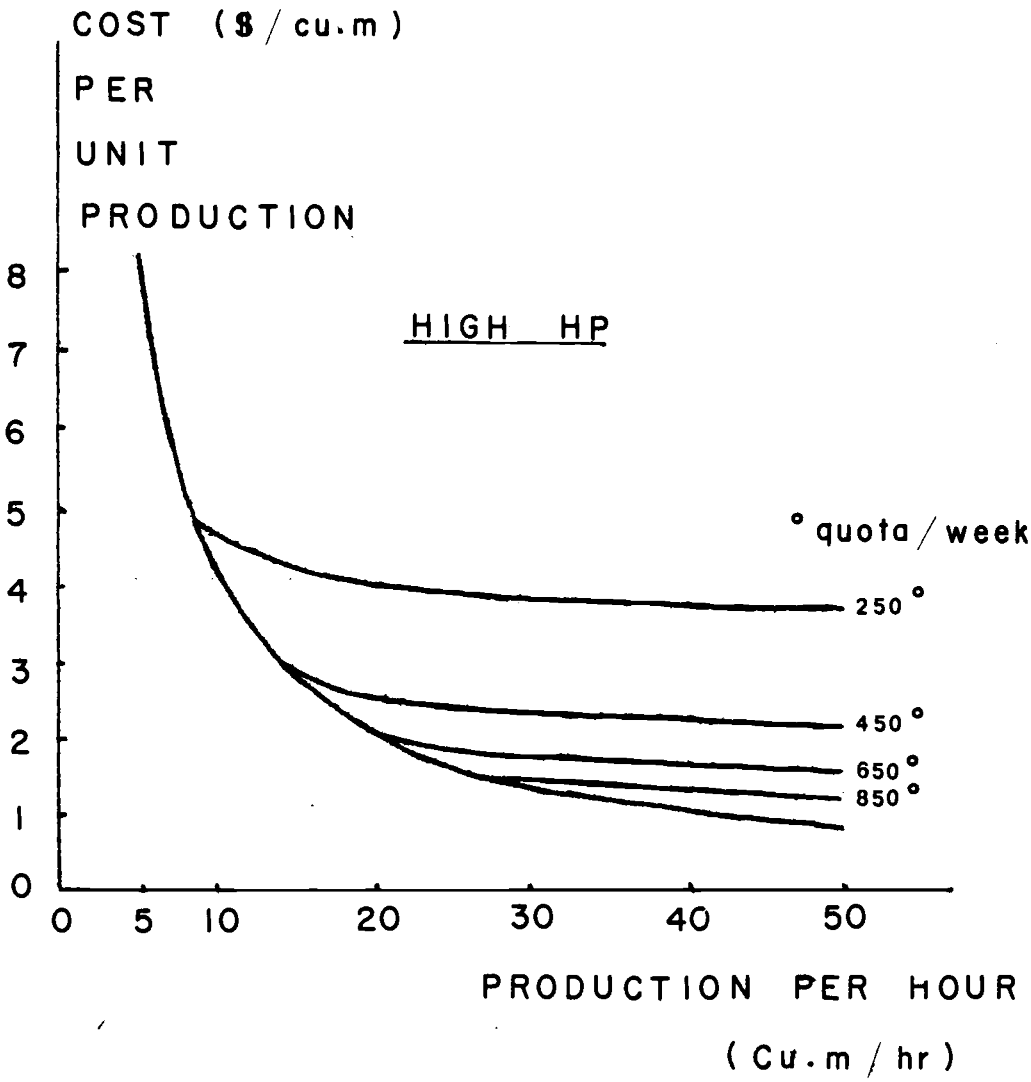
COST – PRODUCTION RELATIONSHIP

FIGURE 24



COST – PRODUCTION RELATIONSHIP

FIGURE 25



COST-PRODUCTION RELATIONSHIP

FIGURE 26

determine the advantage or otherwise of technological changes on a production and cost basis.

Figures 25 and 26 show the influence of imposed quotas on the two horsepower groups.

The salient features are:

1. Large economies of scale in cost saving exist by increasing quotas from 250 to 450 M^3/week. Similarly, but to a lesser extent, increasing quotas further to 650 M^3/week.
2. Beyond 450 M^3/week, due to the nature of the cost curve, the sites available to the machine diminish rapidly as the quota increases, if the machines are to meet production requirements.

The proposed models, in this study, apply to quota-free conditions, as during the study period an upturn in production virtually released all operations from their quota restrictions. Hence, model application is such that the predicted production per hour should be referred to the cost curves to determine suitability of quota level, and also that cost per unit production which applies to the operation quota level.

No doubt the size of the operation will also affect overhead costs, discount rates, etc. and hence total operation costs. However, this is beyond the scope of the present study and as such average costs have been used in machine cost calculation.

For the purposes of clarification, Appendix V outlines the sequence of calculations to be used in final production and cost analysis commencing with actual time study data and finishing with an operator-machine adjusted, delay adjusted estimation of production per hour. In addition, a cost per unit production for a quota level of 250 cu. m per week has been presented to demonstrate the influence of imposed production quotas.

Model Application

1. Planning

Before the proposed equations can be fully utilized as a planning tool, it is necessary to provide some method of readily predicting the number of logs/turn and volume per turn likely under a given set of field contiions. It should be noted that the following predictive equations will apply only to the range of conditions used in this study and the skidding techniques involved. It is preferred that actual field measurements of # logs/turn and volume/turn are used. However, for planning purposes where terrain is yet untraversed, and the logging technique unlikely to change, then predictive equations for these two variables have been determined and are presented below, in addition to a predictive equation for volume/log/turn:

a. $$\begin{aligned} LN(\#\ log/turn) = 2.5866 &+ LN(SYD)\ (m) \\ &+ 0.7213\ LN(Stems/ha) \\ &- 0.2129\ LN(Vol./ha)\ (M^3/ha) \end{aligned}$$

Adjusted R^2 = 0.3858

Variance = 0.1615

b. $LN(Vol./turn) = 2.8663 + 0.2644\ LN(SYD)\ (m)$

$$- 0.2170\ LN(Stems/ha)$$

$$+ 0.7463\ LN(Vol./ha)\ (M^3/ha)$$

Adjusted R^2 = 0.1489

Variance = 0.2508

c. $LN(Vol./log/turn) = 0 - 0.9346\ LN(Stems/ha)$

$$+ 0.9238\ LN(Vol./ha)$$

Adjusted R^2 = 0.3251

Variance = 0.3032

These equations apply to the total horsepower class. As in previous cases, a logarithmic transformation has been used to provide normally distributed residual errors, reduce heteroskedasticity and improve linearity.

To test these equations, information from trials 12 and 13 regarding SYD, volume per hectare and stems/hectare has been used to predict the number of logs and volume per turn for comparison with actual field data. Trials 12 and 13 were two machines working the same area together so the actual volume/turn and number of logs/turn have been averaged.

	Predicted	Actual
# logs/turn	2.86	2.21
Volume/turn	5.81	5.25

The repercussions of this predicted production per hour from such a site, i.e., using the production per hour model as an advance planning tool, are shown below. Incorporating the predicted number of logs and volume per turn results in

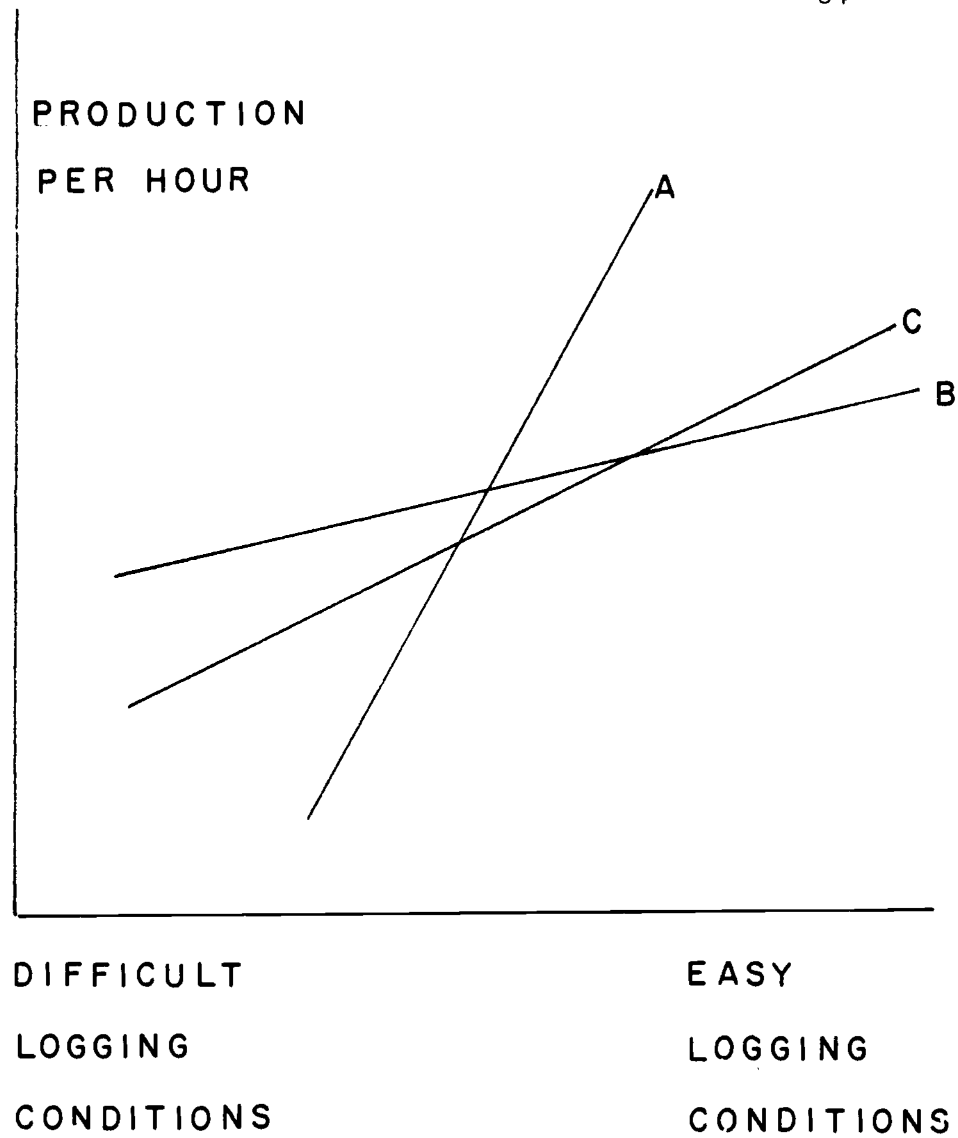
Predicted Production/hour M^3/hour	Actual production/hour M^3/hour
22.58	21.70
19.12 (delay adjusted)	18.38 (delay adjusted)

which are statistically insignificant at the 95% confidence level.

Armed with a predicted production per hour it is a relatively easy task to determine cost of production and hence viability and suitability of this logging equipment.

2. Machine Selection

For this study, the two horsepower sizes proved the same in production response to site conditions, despite large operating cost differences. This naturally has implications for future machine selection. In this case, the technological advantages (if any) of the more expensive machine have not balanced the increased costs on a production per hour basis. In addition, this appears consistent over a wide range of site conditions. By expanding this type of model to include a wider range of machine types direct comparison and analysis of machinery is possible. For instance, consider Figure 27 where for the purposes of explanation, linearity is assumed. Machine A could be highly specialised for high output on good sites but severely affected by declining logging potential, e.g. a tree harvester with increasing slope. Machine B could represent a machine not greatly affected by declining logging



PRODUCTION – LOGGING CONDITIONS

– 3 MACHINE TYPES

FIGURE 27

potential, e.g. high lead yarder. Machine C has similar production rates as machine B, but could be influenced by declining logging potential at a faster rate, e.g. ground contact machinery.

Using the relevant predictive equations it is no problem to provide a comparative model for decision making regarding machine selection, machine pool composition, etc.

Such a decision making process is given in Appendix IV where the production data from an FMC 210CA trial (Wilson, unpub.; Wilson, Kerruish and Moore, 1980) associated with given site conditions, has been compared to the predicted production of rubber tired skidders. Site 1, featured a very large number of stems per hectare with a very small stem size, which caused particular difficulty for the FMC due to its reduced manoeverability. It was anticipated that the articulated and smaller rubber tired skidder would overcome this problem. The results indicate that indeed the cost per M^3 of the FMC was far in excess of the rubber tired skidders, prohibiting the selection of this machine for this particular site on a cost and production basis.

Trial 2 was characterized by a low number of stems per hectare with very large log sizes. Soil conditions were wet. The results indicate that the FMC was able to take full advantage of the large log size plus maintain high speed skidding. Costs were comparable to the low horsepower skidders while high horsepower skidders were prohibitively expensive.

It is granted that there are other considerations in selecting machinery such as the environmental impact and reliability, etc. However, the example just completed does provide a measure of informed machine selection and also a useful planning tool. For example, it is now apparent that given an adjusted forest inventory (i.e., including the relevant logging factors), some prediction of the required machine balance between the number of FMC 210CA skidders and rubber tired skidders is possible. Similarly, having predicted the production per hour for each operation the scheduling of log trucks, estimates of operation duration, and control information (individual road use intensity, etc.) are readily available.

By expanding the model to include a wider range of machinery and to also include those relevant site conditions in normal forest inventory, then the total model will allow:

1. The determination of the required machinery pool both in terms of number and type for the most cost efficient logging operation.
2. Estimates of future logging costs.
3. Estimates of total forest resource actually available to the current and future machine pool.
4. Estimates of likely production rates from the machine pool and also for individual machines and sites.
5. Sound and timely advice to contractors on when to purchase machinery and of which type.

6. Sound contractor management e.g. contractors remain on sites within range of their machinery and quota level.
7. Production quota levels to be adjusted to balance site conditions if so desired and the contractor payment scheme (based on logging potential) used to balance the shortfall or windfall of production. Figures 25 and 26 show the influence of quota level on limiting those sites available under a given quota level. For example, note that a high quota levels (850 M^3/week) only those sites of production potential of 29 M^3/hour (low HP) and greater are available in order to meet production demands.
8. Maintenance of an informed management, aware of those factors affecting logging potential through a useful planning and operations tool. Problem areas are readily identified before machines are on site and planning can then alleviate any difficulty.

CONCLUSIONS AND RECOMMENDATIONS

Production and cycle time predictive equations have been presented as a result of this study, for two horsepower groups, plus a combination of both, within the rubber tired skidder machine class. Statistical tests indicated no significant difference (95% confidence level) between the two horsepower groups in predicted production and cycle time, over the range of sites studied. Hence, it is recommended that attention be centered on the Total HP equation as a predictive base.

Additional investigation has revealed significant differences between operators and/or machines on a production basis, and accordingly an adjusted equation has been presented for the Total HP group. While no significant difference (95% confidence level) has been found between the equations (Total HP; cycle time; production per hour (ACCESS); production per hour (Soil Condition); and production per hour-operator/machine adjusted) it is anticipated that the last, by virtue of an improved adjusted R^2 value and variance of the error term, plus a decreased MSE, would provide the best estimate of production per hour. Hence, it has been used as the basis for equation application in this study.

Using the appropriate equation in combination with machine cost information, provided a prediction of cost per unit production, vital in viability, budgeting and control considerations.

Application of the equations can be on a day-to-day basis to identify and quantify problem logging areas. Likewise the equations can be readily applied to a long-term planning role, after first predicting the number of logs/turn and volume/turn using the equations provided. Hence, it is strongly recommended that in the future, forest inventory should include:

Volume/hectare

Access

Soil condition (short term)

Stems/hectare

Furthermore, for each logging block an average SYD should be calculated. When blocks are not yet defined an average SYD based on previous management practice (road density, etc.) should be used.

The study also concluded that for the range of sites studied, there is no advantage, on a production per hour basis, in selecting a high horsepower (>150 SAE hp) skidder. In addition, the study indicated that for certain sites alternative machinery (FMC 210CA) was compatible (cost per unit production) with the rubber tired skidder group.

The influence of production quotas on profit potential and their interaction with logging potential has been demonstrated. It is suggested that production quota levels be managed with respect to information provided by the proposed equations (logging potential or predicted production per hour).

With regard to future studies it is recommended that:

1. Additional machines be included in the model to greatly increase utility in the machine selection process. A broader machine base will also allow improved prediction of the required balanced machine pool.
2. Further sites be included in the time studies.

3. Those machine costs that change with site conditions be delineated for incorporation into cost analyses.
4. Continued investigation is warranted into an operator evaluation system, both for personnel management and accurate production study purposes.

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APPENDICES

APPENDIX I

Total working hours

8 hours x 5 days x 48 weeks = 1920 hours

1920 hours x .697 (utilization) = 1338 hours

= 1340 hours

*0.697 utilization rate is that derived from this study.

APPENDIX II

Model Validation I

Trial 12. Clark 668

Conditions

SYD	490 M
Vol./turn	6.8 M^3
# logs	2.21
Vol./ha	175.5 M^3/ha
Access	Good
Stems/ha	95
Soil	Dry

Average cycle time = 15.3 minutes

Actual field production = 26.67 M^3/hour or

22.53 M^2/hour delay adjusted

(.847 delay conversion)

1. Production per hour model (total HP model)

   Predicted production = 26.09 M^3/hr (geometric mean)

   = 26.91 M^3/hr (arithmetic mean)

   = 22.79 M^3/hr delay adjusted

2. Cycle time (ACCESS model)

   Predicted cycle time = 15.63 minutes (geometric mean)

   $\frac{60}{15.63}$ x 6.8 = 26.10 M^3/hr (geometric mean)

   = 26.92 M^3/hr (arithmetic mean)

   = 22.80 M^3/hr (delay adjusted

3. Cycle time (soil condition model)

   Predicted cycle time = 15.57 minutes (geometric mean)

   $\frac{60}{15.57}$ x 6.8 = 26.20 M^3/hr (geometric mean)

   = 27.02 M^3/hr (arithmetic mean)

   = 22.89 M^3/hr delay adjusted

APPENDIX II (cont'd)

4. Operator-machine adjusted model

Predicted production = 26.58 M^3/hr (geometric mean)

= 27.35 M^3/hr (arithmetic mean)

= 23.17 M^3/hr delay adjusted

Model Validation II

Trial 13 — Standard Operator

Conditions

SYD	474 M
Vol./turn	3.7 M^3
# logs	1.92
Vol./ha	175.5 M^3/ha
Access	Good
Stems/ha	95
Soil	Dry

Average cycle time = 13.6 minutes

Actual field production = 16.32 M^3/hour or

= 13.82 M^3/hour delay adjusted

1. Production per hour model (total HP model)

Predicted production = 16.24 M^3/hr (geometric mean)

= 16.74 M^3/hr (arithmetic mean)

= 14.18 M^3/hr delay adjusted

2. Cycle time (ACCESS model)

Predicted cycle time = 13.67 minutes (geometric mean)

$\frac{60}{13.67}$ x 3.7 = 16.25 M^3/hr (geometric mean)

= 16.76 M^3/hr (arithmetic mean)

= 14.20 M^3/hr delay adjusted

APPENDIX II (cont'd)

3. Cycle time (soil condition model)

Predicted cycle time = 13.63 minutes (geometric mean)

$$\frac{60}{13.63} \times 3.7 = 16.28\ M^3/hr \text{ (geometric mean)}$$

$$= 16.80\ M^3/hr \text{ (arithmetic mean)}$$

$$= 14.23\ M^3/hr \text{ delay adjusted}$$

4. Operator adjusted model

Predicted production = 16.41 M^3/hr (geometric mean)

= 16.85 M^3/hr (arithmetic mean)

= 14.27 M^3/hr delay adjusted

APPENDIX III

Machine Costs ($Aust)

Low horsepower

Vo	average purchase price	$70,000
n	loan period	3 years
t	# annual payments	12
i	interest rate	10%
d	depreciation period	

8 hours x 5 days x 48 weeks x 4 years = 7680 hours

actual possible working hours

(7680)(.697) = 5353 hours

≈ 1338 hours/annum

$$\text{Periodic payment} = \frac{Voi(1+i)^{nt}}{(1+i)^{nt}-1}$$

$$= \frac{(70{,}000)\left(\frac{.10}{12}\right)\left(1+\frac{.10}{12}\right)^{3x12}}{\left(1+\frac{.10}{12}\right)^{3x12}-1}$$

$$= \$2259$$

$$\text{Internal cost} = \frac{(2259)(3)(12) - (70{,}000)}{5353}$$

$$= \$2.12$$

Operating costs = running cost[1] + interest cost + labor cost[2]

Administration costs = 10% (operating costs)

APPENDIX III (cont'd)

Operating Costs	$/hour
Fuel, maintenance	$ 8.43
Insurance[3]	1.79
Interest	2.12
Labor	10.00
Depreciation	7.48
	$29.82
Administration costs	
(.10)(29.82)	2.98 (70% fixed cost component)
Total cost	$32.80/hour

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[1]Includes depreciation (salvage price = 1/2 purchase price), insurance and maintenance

[2]$10.00/hour

[3]$3.00 for every $100 value

APPENDIX III (cont'd)

High horsepower

As on previous page except purchase price = \$101,000

$$\text{Periodic payment} = \frac{(101{,}000)\left(\frac{.10}{12}\right)\left(1+\frac{.10}{12}\right)^{3\text{x}12}}{\left(1+\frac{.10}{12}\right)^{3\text{x}12}-1}$$

$$= \$3259$$

$$\text{Interest cost} = \frac{(3259)(3)(12) - 101{,}000}{5353}$$

$$= \$3.05$$

Operating Costs	\$/hour
Fuel, maintenance	\$11.18
Insurance	2.59
Interest	3.05
Labor	10.00
Depreciation	10.79
	\$37.61

Administration costs

(.10)(3761)		3.76 (70% fixed cost component)
	Total cost	\$41.37/hour

APPENDIX IV

FMC

SYD	100	432
Vol./turn (M^3)	4.37	11.33
# logs	2.33	1.9
Vol./ha (M^3/ha)	230.94	263.45
ACCESS	Good	Good
Stems/ha	170	70
Dry soil	Dry	Wet
Topography	15%	15% downhill loaded
Actual production (M^3/hour)	20.44	43.27
(delay adjusted) x .847	(17.31)	(36.65)

1. Predict # logs/turn and volume/turn for rubber tired skidder.

   Predicted # logs/turn = 2.84 (trial area 1)

   = 2.06 (trial area 2)

   Predicted volume/turn = 3.66 (trial area 1)

   = 7.21 (trial area 2)

2. Predict production per hour (using total cycle time--soil condition equation)

   Predicted production/hour--trial area 1

   = 28.06 M^3/hr

   = 23.77 (delay adjusted)

   Predicted production/hour--trial area 2

   = 30.07 M^3/hr

   = 25.47 (delay adjusted)

APPENDIX IV (cont'd)

3. Machine costs ($Aust)

a. FMC

$$\text{Periodic payment} = \frac{123{,}000\left(\frac{.10}{12}\right)\left(1+\frac{.10}{12}\right)^{3x12}}{\left(1+\frac{.10}{12}\right)^{3x12}-1}$$

$$= \$3969$$

$$\text{Interest cost} = \frac{(3969)(3)(12) - 123{,}000}{5353}$$

$$= \$3.71$$

Running cost		$31.72
Interest cost		3.71
Labor cost		10.00
Administration		4.54
	Total	$49.97

b. Low horsepower	32.80
High horsepower	41.37

4. Comparison

Trial 1	Cost/M^3	Production/hour (delay adjusted)
FMC	2.89	17.31
Low HP	1.38	23.77
High HP	1.74	23.77
Trial 2		
FMC	1.36	36.65
Low HP	1.29	25.45
High HP	1.63	25.45

APPENDIX V

Hyopthetical case		Source
Av. SYD (m)	250	Calculated or estimated
Av. Vol./turn (cu. m)	2.98	Predicted
Av. # logs/turn	2.30	Predicted
Vol./ha (cu. m/ha)	182.4	Measured or estimated
Access (good = 1)	good	Measured or estimated

1. Production per hour (operator-machine adjusted) is given by:

   LN (production/hr) = 2.7827 + 0.8623 LN(Vol./turn)

   error variance = 0.06792 − 0.3607 LN(SYD)

   − 0.2469 LN(# logs/turn)

   + 0.2262 LN(Vol./ha)

   + 0.1018 ACCESS

   = 16.55 cu. m/hour

2. Logarithmic mean value conversion (Baskerville, 1972)

   $$= \text{LN } (16.55) + \frac{0.05792}{2}$$

   = 17.04 cu. m/hour

3. Delay adjusted production

   = 17.04 x 0.847

   = 14.43 cu. m per productive hour

   The study shows that 85% of the working day is potential production time

   → 8 hours x 0.85 = 6.8 hours

   6.8 hours x 14.43 = 98.12 cu. m/day

APPENDIX V (cont'd)

4. Cost consideration 1 using unrestricted production and assuming a low HP skidder class:

Hourly cost = \$32.17/hour

Predicted hourly production = 14.43 cu. m/hour

$$\rightarrow \text{Cost/cu. m} = \frac{32.17}{14.43}$$

$$= \$2.27/\text{cu. m}$$

5. Production quota = 250 cu. m/week

$$\text{Productive hours required} = \frac{250}{14.43} = 17.33 \text{ hours}$$

Productive hours available = 40 x .85

= 34.0 hours

Idle hours = 34.0 - 17.33 = 16.67 hours

$$\text{Machine cost} = \frac{\dfrac{\text{Fixed cost/hr}}{17.33/34.0} + \text{variable cost/hour}}{14.43 \text{ cu. m/hr}}$$

$$= \frac{\dfrac{23.39}{17.33/34.0} + 9.32}{14.43}$$

$$= \$3.83 \text{ per cu. m}$$

i.e. Unrestricted production, cost = \$2.27/cu. m

250 cu. m/week quota, cost = \$3.83/cu. m