PREDICTION OF TIMBER HARVESTING PRODUCTIVITY FOR SEMI-MECHANISED SYSTEMS IN VIPHYA FOREST PLANTATIONS, MALAWI

by

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DECLARATION

I hereby certify that this thesis is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this thesis.

Signed ________________________________

Elisha Stephen Ngulube

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DEDICATION

This work is dedicated to my parents, Stephen Ngulube and Modester Moyo, for their strong ambition and conviction towards better education.

ABSTRACT

At least 200,000 m^3 of timber are harvested annually using semi-mechanised harvesting systems (SMS) on the Viphya forest plantations in Malawi. Although these systems have long been used on the Viphya, no investigation on their productivity has so far been reported. The absence of local productivity models created uncertainty about the importance of site-based factors that influence timber harvesting productivity of these systems on the Viphya. Secondly, there is paucity of information regarding the appropriate timber harvesting systems for production maximisation and cost minimisation. This study aimed to develop prediction models for estimating the productivity and costs of semi-mechanised and simulated mechanised timber harvesting systems on the Viphya forest plantations.

The study was conducted in *Pinus kesiya* stands at Kalungulu and Champhoyo forest stations of the Viphya forest plantations. A work study approach was followed to capture harvesting time and volume data. Stepwise multiple regressions were used to develop felling time models for a chainsaw over tree size, inter-tree distance, slope, ground condition, brush density, and ground roughness; and skidding time models over distance, slope, ground condition, ground roughness and volume skidded per cycle for a grapple skidder. Models were statistically validated. Secondary work study data for semi-mechanised systems were simulated for mechanised productivity based on local site factors.

The study had shown that diameter at breast height and inter-tree distance were important factors that best explained felling time prediction models in *Pinus kesiya* stands on the Viphya forest plantations. Similarly, distance from stump to the roadside landing was the most important factor in addition to volume load, slope and ground conditions that determined grapple skidding time.

Mechanised systems appear to be more advantageous than semi-mechanised systems. The former are associated with lower operating costs and inventories with relatively high production rates. Therefore, mechanised systems could help to optimise timber harvesting productivity on the Viphya. Further studies should be conducted to determine the effect of different ground conditions and roughness on skidding productivity.

Keywords: Extraction, semi-mechanised, timber harvesting, time study, Viphya forest.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

UNITS OF MEASURE

1 inch (in)	2.54 centimetre (cm)
1 foot (ft)	0.305 metre (m)
1 cubic foot (ft^3)	0.028 cubic metre (m^3)
1 ton (t)	0.94 cubic metre (m3) (Pines and *Eucalyptus grandis*)
1 centi-minute (cmin)	0.01 minute (min)
1 United States Dollar ($)	250 Malawi Kwacha (MK)
1 United States Dollar ($)	8.50 South Africa Rand (ZAR)

CHAPTER 1: INTRODUCTION

The Viphya forest plantations cover 53,500 ha of forest land. A total of 20,000 ha of the area is managed by Raiply (Malawi) Limited under a concession arrangement. In terms of species composition, *Pinus patula* represents 80% by area followed by *P. kesiya* (8%), *P. elliottii* (7%), *Eucalyptus* (4%) and minor species (1%). The plantations are a focal point for industrial timber harvesting operations in Malawi as most of the forest stands in the plantations have matured and some have even over-matured (Luhanga, 2009).

A total estimate of 310,000 m^3 is harvested annually in the form of timber, transmission poles and firewood from the Viphya using various harvesting systems (Chipokosa, 2011). However, physical site checks indicated that this total volume may be somewhat underestimated compared to reality. Groups of small scale industries tended to harvest more than the major forest industry (Raiply) which has concessionary rights in the area. It is estimated that Raiply harvests about 200,000 m^3 of round wood per year, using semi mechanised harvesting systems.

Presently, mechanised harvesting systems are not yet available on the Viphya forest plantations. Evanson and McConchie (1996) credited mechanised systems for their safety to the harvesting personnel. Wang *et al.* (2004) indicated that high initial costs of mechanised systems become unnecessarily prohibitive for small scale harvesting contractors in spite of their well-known high productivity levels in harvesting. However, Egan and Baumgras (2003) argued that mechanised systems become less effective where large diameter and irregular terrain exist. Unfortunately, manual systems have grossly been criticised as wasteful and therefore least productive for commercial harvesting (Luhanga, 2009). Hence, semi-mechanised harvesting systems (involving chainsaws, skidders, loaders and trucks) remain important due to their versatility in the forest and their associated low initial costs (Lortz *et al.*, 1997; Parker & Bowers, 2006).

Although semi-mechanised harvesting systems have been used since late 1980's on the Viphya forest plantations, no investigation on their productivity has so far been reported. However, studies associated with semi-mechanised systems have extensively been reported from other parts of the world. Lortz *et al.* (1997) conducted a study in western Arkansas, United States on motor-manually felling and productivity of shortleaf pine (*Pinus echinata*

Mill.) and loblolly pine (*P. taeda* L.). A work study was used to determine elemental times of tree felling and processing. Step wise regression models were used to determine estimator variables. It was reported that tree size principally affected the felling time. In the Caspian *Fagus orientalis* L. dominated hardwood forests of Iran, a work study revealed that the productivity of motor-manual felling was mainly affected by tree size and inter-distance (Behjou *et al*., 2009). Similar results were reported by Wang *et al*. (2004) in West Virginia, United States on the Appalachian hardwoods. The hardwood species under study comprised *Quercus rubra, Betula lenta, Acer rubrum, A. saccharum, Tilia americana* and *Q. prinus*. In western Uganda, Balimunsi *et al*. (2011) reported a comparative analysis of harvesting productivity of *P. patula* softwoods at Mafuga forest plantation. Time studies were used to determine felling productivity. There are physiological differences between hardwood and softwood groups of timber, that appear to cause within group variation to be less sensitive to felling time (Lortz *et al*., 1997; Ghaffarian & Sobhani, 2007).

Sabo and Porsinšky (2005) determined the productivity of a Timberjack 240C cable skidder in *Fagus sylvatica* L. and *Abies alba* Mill. round wood at Delnice forest in Croatia using a work study approach for 16 days to establish time and operational variables. The study showed that skidding distance and number of logs choked were the main factors affecting total skidding time. Spinelli and Magagnotti (2011) also used work study techniques to predict the productivity, cost and energy consumption of a farm tractor and a sulky in central Italy and found that piece size, winching distance, tractor power, skidding distance and number of assistants affected the skidding tractor's productivity.

In general, most studies embrace work study as an appropriate tool for estimating and predicting timber harvesting systems cost and productivity (McNeel and Dodd, 1997; McDonald & Fulton, 2005). This is because work study enables a careful analysis of the factors affecting productivity and the associated costs (Nott, 1983; Wang, 1994; Polander, 1998). Therefore, site-machine matching is a precursor to the efficiency of volume production and cost minimisation (Brunberg *et al*., 1989; Johansson, 1997).

The study site (Raiply) uses chainsaws, 360D Timberjack cable skidders, 525C CAT grapple skidders and Bell three-wheel loaders to conduct harvesting operations. Each skidder has its own landing from where a long-haul truck loads logs for transportation to the mills. Two choker-men are assigned in a compartment and one dechoker to each cable skidder. One assistant is assigned to a grapple skidder in the compartment to direct and point where felled trees are lying. The current practice is that two chainsaws are assigned to each of the two skidders. Trucks make five trips per day and all other machines work for an 8-hour day shift.

1.1 Problem statement

The absence of prediction models to estimate machine productivity and costs renders inefficient execution of logging operations (Akay, *et al.*, 2004). Current techniques of quantifying machine productivity in the Viphya tend to overlook the significance of site-based logging factors that affect productivity. Secondly, there is paucity of information regarding the appropriate combinations of timber harvesting systems. Consequently, cost implications on operations become enormous when information is generalised and misaligned (Kluender *et al.*, 1997; Applegate *et al.,* 2004).

1.2 Main objective

The general objective of the study was to develop prediction models for estimating the productivity and costs of semi-mechanised and simulated mechanised timber harvesting systems in the Viphya forest plantations.

1.2.1 Specific objectives and associated research questions

The following specific objectives and associated questions were developed to achieve the general objective of the study:

Specific objective 1: To select site-based factors of influence on chainsaw felling time.

a) What site-based factors in *Pinus kesiya* stands influence chainsaw felling time?
b) What is the model for estimating timber felling time based on site factors?
c) How valid is the model in predicting predicted felling time?

Specific objectives 2: To select site-based factors of influence on skidding time for a grapple skidder.

a) What site-based factors in *Pinus kesiya* stands influence grapple skidding time?
b) What is the model for estimating timber skidding time based on site factors?
c) How valid is the model in predicting predicted skidding time?

Specific objective 3: To compare the production rates and costs of chainsaw-grapple skidder and feller buncher-grapple skidder systems.

a) Are there any differences in production rates and costs between feller buncher-grapple skidder and chainsaw-grapple skidder harvesting systems on Viphya forest plantations?

1.3 Justification

Pinus kesiya and *P. elliottii* are the most important prime wood species for veneer production in the Viphya forest plantations. The species are generally characterised by light branching compared to *P. patula*. As such, *P. patula* is mainly used for saw timber production in the Viphya.

There is need to investigate techniques of forecasting machine productivity and costs using significant site decision variables for Viphya. Such decision variables are important in setting realistic daily production targets (Stevenson, 1996) for the operations. This is particularly important with the ever increasing demand for raw materials (logs) at the mill.

The information generated would facilitate decision making processes for identifying critical activities, inputs and outputs (Kühmaier & Stampfer, 2010). Such information is vital for optimisation of productivity of timber harvesting systems in the ever changing operating environment. Harvesting systems would be redesigned to reduce delays or improve on efficiencies. Logging managers would be able to cost their production more accurately based on the realistic standard times.

CHAPTER 2: LITERATURE REVIEW

In this section, a review is made of various studies pertaining to timber harvesting operations, work study methods and productivity. A discussion is made on the application of time studies on harvesting operations and their relationship to costs. Different methodologies and analytical approaches are reviewed.

2.1 Timber harvesting

The terms timber harvesting and timber logging are generally used synonymously in forest engineering (Burton, 2008). Timber harvesting encompasses all the activities undertaken to convert a standing tree into utilisable products delivered at the mill or other end user (Wenger, 1984). Examples of timber products include poles, logs, chips and firewood (MacDonald & Clow, 2010). According to RCA (1992) timber harvesting precisely involves harvest planning, tree felling, debranching, cross cutting, extraction and site rehabilitation after harvest.

A timber harvesting operation is accomplished by making use of harvesting systems and harvesting methods (Silayo *et al.*, 2007). However, some literature uses harvesting systems and harvesting methods interchangeably (Ghaffarian *et al.*, 2007; Eggers *et al.*, 2010; Lehtimäki & Nurmi, 2011). In this study, a distinction is made between harvesting systems and harvesting methods.

2.1.1 Harvesting systems

"A harvesting system refers to tools, equipment and machines to harvest an area," according to Pulkki (1997). Generally, manual, animal-motor-manual, semi-mechanical and mechanised harvesting systems exist in commercial tree harvesting and timber transport (de Wet, 2000).

Harvesting systems are selected based on environmental, technological and socio-economic feasibility in relation to site factors (MacDonald, 1999; Grobbelaar, 2000a). According to Silayo *et al.* (2007), such factors as terrain, tree size, climatic conditions and skill of operators influence systems selection. In the Viphya forest plantations, common harvesting systems include manual and semi-mechanised.

2.1.2 Harvesting methods

Pulkki (1997) defined harvesting methods as the assortments or form in which wood is delivered to the mill or end user. Common types of harvesting methods are cut-to-length (CTL), tree length (TL) and full-tree (FT) (MacDonald & Clow, 1999). In each of these methods, manual, semi-mechanised or mechanised harvesting systems could be involved in tree felling, debranching, cross-cutting, topping and extraction phases.

In semi-mechanised harvesting methods, trees are severed from their root systems, debranched, cross-cut and topped using chainsaws (Limbeck-Lilienau, 2003; Russell & Mortimer, 2005). In mechanised methods, harvester processors and feller bunchers (mechanised systems) are quickly gaining ground in felling operations (Stokes & Schilling, 1997; Spinelli *et al*., 2007). Harvesters fell, debranch and cross-cut timber into desirable lengths while feller bunchers fell and bunch the trees (de Wet, 2000).

Chainsaws are the most versatile tools for processing large diameter trees and they are not limited by ground physical conditions such as slope as opposed to mechanised felling (Burton, 2008; Behjou *et al*., 2009). However, felling direction remains a challenge to facilitate extraction (RCA, 1992). On the other hand, mechanised equipment are characterised by high initial costs making them inaccessible for small logging contractors (Naudé & Nagel, 2010). As such, the decision and location to cross-cut or debranch a tree may vary depending upon the type of harvesting systems (tools, equipment machines) that are in place (Pulkki, 1997).

For instance, in a CTL method, the tree is felled, debranched and cross-cut into short assortments at the stump area or at the landing (Kembel *et al*., 2008). Short log assortments are extracted using forwarders or non-articulated trucks to the landing or mill. The method is particularly popular where small diameter logs and mechanised harvesting systems are present (Gellerstedt & Dahlin, 1999; Bolding & Lanford, 2002). However, manual CTL methods are used in the Viphya forest plantations among *in-situ* pit sawing contractors. Large diameter logs are processed infield using axes or chainsaws and rolled manually to the sawing deck for conversion into rough sawn timber.

In tree length methods, felling, debranching and topping are carried out within the compartment (Guimier, 1999) where chainsaws and feller bunchers are ideal for converting trees into a TL. Cable, grapple and clambunk skidders are the primary machines used in the transportation of tree lengths from stump area to the landing (Eggers *et al*., 2010). This method is seldom used in harvesting pine but common in *Eucalyptus* (for transmission poles) on the Viphya forest plantations. Cable and grapple skidders are used for primary transport where cross-cutting of logs into required product specifications is carried out at the landing and mill.

The other method is full-tree. Pulkki (1997) and Eggers *et al.* (2010) indicated that FT method involves extraction of wood (logs) with branches and tops from the stump area to the landing. Felled trees are mechanically or manually debranched at the roadside (landing) (Kembel *et al*., 2008). It is, therefore, clear from this method that huge volumes of slash accumulate at the landing area posing environmental challenges (e.g. fires). However, this method is widely used in harvesting pine timber on the Viphya forest plantations using semi-mechanical systems. As the skidders drag (extract) felled trees, most of the branches get removed on the way due to ground friction. It is envisaged that chainsaw costs associated with debranching are viably reduced by the time the felled tree is processed at the roadside landing.

In a FT method, all types of skidders are applicable for extraction operations to the landing (Pulkki, 1997). However, absence of self-loading mechanisms makes cable skidders less competitive to grapple skidders (Behjou, *et al*., 2008). In fact Kluender *et al*. (1997) found that grapple skidders had shorter extraction cycle times than cable skidders on similar harvesting sites. Fig. 2.1 shows a grapple skidder extracting *Pinus kesiya* logs in the Viphya forest plantations in Malawi using a full-tree method.

Fig. 2. 1. CAT 525C Grapple Skidder extracting *Pinus kesiya* logs in the Viphya forest plantations

With regard to terrain, Jourgholami and Majnounian (2011) indicated that wheeled cable skidders can effectively be used on more gentle and on designated skid roads in steeper terrain. Although, wheeled skidders are more effective in downhill slopes of <35%, clambunk skidders, in particular, have a wider effective slope range of up to 60% (MacDonald, 1999).

Erasmus (1994) classified terrain according to ground conditions, ground roughness and slope on scales of 1-5, 1-5 and 1-7, respectively (see Table 2.1). For instance, a scale of 1 for ground conditions implies that the soils are dry enough for trafficability and the conditions deteriorate as the scale approaches 5. Soil moisture content is the main criterion used in assessing ground conditions. Ground roughness is defined based on the presence of obstacles. Slope is described by its magnitude, i.e. from level to very steep.

Table 2. 1. National terrain classification system

Ground condition	*Ground roughness*	*Slope (in percent)*
1. Very good	1. Smooth	1. Level (0-10%)
2. Good	2. Slightly uneven	2. Gentle (11-20%)
3. Moderate	3. Uneven	3. Moderate (21-30%)
4. Poor	4. Rough	4. Steep 1 (31-35%)
5. Very poor	5. Very rough	5. Steep 2 (36-40%)
		6. Steep 3 (41-50%)
		7. Very steep (> 50%)

Adapted from Erasmus (1994).

2.2 Timber resource estimation

Timber and land resources are important assets of forest owners and thus necessitate forest owners to estimate the volume of standing timber on their land at the lowest cost and with the least effort (Bredenkamp, 2000b). Wood processing industries are particularly interested in log volume estimation which must be as accurate as possible (Bredenkamp, 2000a; West, 2009) to guarantee a return on investment. In terms of procedures for volume estimation, a distinction is made between standing trees and logs.

2.2.1 Standing volume

It is not practical to assess volume of every individual tree in compartment. Hence sample plots are made based on the size of the compartment. A standard plot is about 0.04 ha and sampling intensities in the range of 5-10% are recommended (Bredenkamp, 2000a). However, intensities of 3% are used for generating general forest stand management information.

Volume estimation of standing trees is determined by use of such parameters as basal area at 1.3-1.4 m above ground (breast height), height and a form factor (West, 2009). Diameters of all trees in a plot are calibrated at breast height from the upper side of the slope to the nearest millimetre using calipers or diameter tapes. Corresponding tree heights are sampled and captured using the angle of elevation and angle of depression with a clinometer or a hypsometer. Linear distance corresponding to the height of the tree being measured is determined using a linear tape or range finders (Avery & Burkhart, 2002). However, this approach in latest tree measuring equipment does not apply. Modern equipment make use of the laser light technology to calibrate tree heights.

In terms of sampling intensity, Bredenkamp (2000a) recommends that a minimum sample size of thirty trees for height-diameter pairs must be measured per management unit (compartment). This is based on the central limit theorem of probability which states that the mean of at least thirty independent observations obtained from the same population returns a normal distribution (Husch *et al.*, 2003; MFNRO, 2012).

In predicting standing tree volume, multiple regression analyses are used to determine the estimator variables. Since tree stems are not truly cylindrical, form factors are often used (West, 2009). Table 2.2 shows examples of three main categories of the models commonly used in estimating tree volume.

Table 2. 2. Standing tree volume models

Constant form factor	$V = b_1 dbh^2 H$	Equation 2.1
Combined variable	$V = b_0 + b_1 dbh^2 H$	Equation 2.2
Logarithmic Schumacher and Hall	$\ln V = b_0 + b_1 \ln(dbh + f) + b_2 \ln(H)$	Equation 2.3

Notation:

V	= volume in m^3,
dbh	= diameter at breast height in cm,
H	= total tree height in m,
f	= form factor, and
b_0, b_1, b_2	= regression coefficients.

All equations account for diameter at breast height and height as the two main factors that influence tree volume. Avery and Burkhart (2002) indicated that Equation 2.1 ignores tree form differences that exist between small and big trees in a compartment. The model is ideal for estimating merchantable volumes which logically have negative intercepts. Equation 2.2 takes into account of the form differences between small and big tree diameters because of associated negativity of the intercept (Avery & Burkhart, 2002). When total height is used in estimating total volume, the intercept is typically negative. In contrast, the combined variable and Schumacher and Hall models are useful in estimating total as well as merchantable stem volumes (Clutter *et al*., 1983).

Although log transformations of the Schumacher and Hall model result in volume under-estimates, the model yields superior results of them all (Akindele, 2005; Van Zyl, 2005; Fernández Tschieder *et al*., 2011). As such, Equation 2.3 was appropriate for this study.

2.2.2 Log volume

The volume of felled trees (logs) is commonly determined by use of stem section models under-bark at predetermined intervals to represent the whole range of cross-sectional areas of a tree. Calipers and diameter tapes are commonly used to capture log diameters using a 2-diameter class and linear tapes are used to estimate log lengths (Avery & Burkhart, 2002).

Huber's, Smalian's and Newton's formulae are the commonly used models for estimating the volume of logs (West, 2009). In rare cases, the xylometer method is also used to estimate log volume. The xylometer method uses the Archimedes principle of water displacement in a dish. For these models to estimate utilisable volume (under-bark), it is a common practice to first estimate diameter under-bark of a particular tree species. Table 2.3 shows the list of models used in estimating log volume (Bredenkamp, 2000b).

Table 2. 3. Models used for estimating log volume

Diameter under-bark formula	$d_{ub} = b_0 + b_1 d_{ob}$	Equation 2.4*
Huber's formula	$V_{ub} = \pi \left(\frac{d_{0.5ub}^2}{40000}\right) L$	Equation 2.5
Smalian's formula	$V_{ub} = \pi \left(\frac{D_{ub}^2 + d_{ub}^2}{80000}\right) L$	Equation 2.6
Newton's formula	$V_{ub} = \pi \left(\frac{D_{ub}^2 + 4d_{0.5ub}^2 + d_{ub}^2}{240000}\right) L$	Equation 2.7

* This equation is used to estimate diameter under-bark which in turn is used to determine volume under-bark, according to Cao & Pepper (1986).

Notation:

V_{ub} = volume under-bark in m^3,

D_{ub} = butt diameter under-bark in cm,

$d_{0.5ub}$ = mid-diameter under-bark in cm,

d_{ub} = thin-end diameter under-bark in cm,

d_{ob} = thin-end diameter over-bark in cm, and

L = length in m.

The degree of precision of these models depends on the amount of information utilised to estimate volume (West, 2009). Huber's formula takes into account of mid-point basal area and log length. Generally, the model is less practical but its estimates are considered to be intermediate because it only requires mid-point measurements and assumes that the log has a uniform taper (Avery & Burkhart, 2002). On the other hand, Smalian's model uses thick end (butt) and thin end basal areas and length. Smalian's model is deemed least accurate (about 10% under-estimate) of the three models. However, it is mainly ideal for short log lengths (Wenger, 1984). Newton's formula is used with thick end, mid-point and thin end basal areas and length of a log (Bredenkamp, 2000b). The model gives the best volume estimates for long log lengths but somehow tedious to measure the diameters (West, 2009). Therefore, Newton's model was most appropriate to estimate long log volumes in this study.

2.3 Work study

Work study is a technique in the work productivity science that aims to optimise the use of human and material resources through application of most efficient and effective production approaches. Currie and Faraday (1989) defined work study as a technique that applies method study and work measurement with an aim of improving productivity. Method study and work measurement are distinctive but inter-related concepts of work study.

2.3.1 Method study

Method study is defined as the analysis and examination of existing and proposed ways of doing work (Van Niekerk, 1982). With method study, emphasis is directed towards improvement of methods of doing work while maximising the associated economic gains (Currie & Faraday, 1989). This is particularly important in timber harvesting circles as harvesting technologies are changing all the time. The shift towards mechanisation exacerbates the need for machine operators to holistically optimise production methods that are safe, ecologically balanced and highly productive (Salomaa, 2008). Raiply Malawi Ltd in the Viphya forest plantations is at the verge of embarking on mechanisation evident by introduction of new grapple skidder investments in the concession area.

2.3.2 Work measurement

Björheden (1991) stated that work measurement includes aspects of production environment and work content where the capability of human effectiveness is assessed and established. Work measurement is accomplished by such techniques as time study, synthesis, predetermined motion time system (PMTS), estimation and activity sampling (Currie & Faraday, 1989). According Currie and Faraday (1989):

- Time study refers to a technique of work measurement that is designed to establish time lapse for an activity at a defined standard of performance. Work is broken down into distinguishable and measurable short time tasks called work elements. These elements are usually repetitive (cyclic) and include productive and non-productive (delay) times (Kellogg & Spong, 2004; Spinelli & Visser, 2009). For instance, productive elemental times for grapple skidding may be made up of move to load, grapple load, travel loaded, unload (Kluender *et al*., 1997; Dempster *et al*., 2008). Similarly in a felling operation, Wang *et al*. (2004) showed that work could be divided into walking to tree, acquiring (clearing and judging felling direction), cutting, topping and debranching for a tree length method. Notwithstanding this, productive time has been defined to include time devoted to core output production and short delays of less than 15 minutes (Warkotsch, 1994; Laitila, 2008). Productive elemental times for an average and qualified operator (worker) are rated in order to establish the standard time. According to Niebel and Freivalds (1999), a worker is rated for speed and effectiveness on a work scale of 0-100 percent on the British Standard 3138-1969; where 0 percent denotes inactivity and 100 percent is the standard performance for an average and qualified operator. Exceptional cases exist where a worker is rated more than 100 percent due to exceptional speed and accuracy of work done according to Currie and Faraday (1989). However, such cases do not last for a long period of time. A relaxation allowance is included as a percentage of the basic rated time for each productive element to allow for personal needs and body fatigue caused by the job itself (Kanawaty, 1997). On the other hand, non-productive time in a time study includes such times as work change over, long break or mechanical delays. The overall sum of productive and non-productive time makes up the total shift time (scheduled time).
- Synthesis is a work measurement technique that uses extrapolated time data taken on jobs containing similar elements. Synthetic data for similar jobs and elements are used to derive the work content of the job under study.

- PMTS uses basic human motions in order to establish time for a job at a defined level of performance. The breakdown of work into elements forms basis for work improvement.
- An estimation technique is used when less precise information is required in determining work content. It is mostly based on the knowledge and experience of similar types of work but without detailed breakdown of elements and performance rating.
- Activity sampling is a work measurement technique in which frequencies of work elements are recorded at a predetermined time interval. It allows the observer to discover main features of the work and elements of primary concern such as idle or non-productive elements. The statistical method for determination of preliminary readings is presented in Equation 2.8 (Currie & Faraday, 1989:233) as follows:

$$n' = \frac{4p(100-p)}{L^2} \qquad \text{(Equation 2.8)}$$

where, n' = number of observations (readings) required for a pilot study.

p = percentage of element being studied.

L = accuracy (confidence level) being a percentage.

Some work measurement techniques are used more prominently than others depending on the level of accuracy required (Currie & Faraday, 1989). It is also common to use more than one technique in carrying out work measurement. For instance, an activity sampling can be used to precede a time study or better still; a synthesis technique can be used in the absence of an appropriate machine which has similar work processes and elements. Commonly used equipment in work measurement includes Husky Hunter computers (Lageson, 1997; Spinelli & Visser, 2009), stopwatches (Silayo *et al*., 2007; Behjou *et al*., 2009) and videos (Björheden, 1998; Eker *et al*. 2011). Time is commonly measured in centiminutes.

2.3.3 Sample size determination

Niebel and Freivalds (1999) indicated that activity sampling is useful (95% or 95.45% confidence level) in determining the number of observations for a work study using a statistical method. Kanawaty (1997) presented the following statistical method (Equation 2.9) for work study sample size determination:

$$n = \left(\frac{40\sqrt{n'\sum x^2 - (\sum x)^2}}{\sum x}\right)^2 \qquad \text{(Equation 2.9)}$$

where, n = number of observations required for work study.

n' = number of observations taken for a pilot study.

x = value of the observations.

The statistical method is based on the premise that a pilot study is conducted in order to confirm the appropriate number of samples. Hence, Kanawaty (1997) indicated that the statistical method of determining the sample size is quite reliable. In any case, the existing variations in readings are due to mere chance (random) and not intentional. For instance, Mousavi *et al*. (2012) used 58 samples in evaluating full-tree skidding by an HSM-904 skidder in Northern Iran. Behjou *et al*. (2009) determined 129 cycles for a felling operation study. However, in practical terms, the appropriate number of samples would largely depend on the local timber harvesting site factors.

Notwithstanding this, some work study analysts use conventional methods for the number of cycles (observations) to be made based on total number of minutes per cycle. The following guide (Table 2.1) is an example for determination of number cycles (Kanawaty, 1997: 294):

Table 2. 4. Number of recommended cycles for time study

Description	Magnitude										
Min/cycle	<0.1	<0.25	<0.5	<0.75	<1	<2	<5	<10	<20	<40	>40
No. of cycles recommended	200	100	60	40	30	20	15	10	8	5	3

From Table 2.4 it clearly shows that the shorter the cycle time the more the cycles recommended for a time study. However, it is imperative that an adequate sample be collected for meaningful statistical inference of the study.

The derivation of number of samples in statistical methods of Equations 2.8 & 2.9 seems to account for reality of the scenario since direct observations are applied. In contrast, conventional methods (Table 2.4) use indirect observations (extrapolations) from similar work to derive sample size. Considering the advantages of these methods, the statistical method was deemed appropriate for application in the Viphya study.

2.4 Work study procedure

Work study uses a systematic procedure in examining and analysing work processes. Kanawaty (1997) pointed the following steps involved in conducting a successful work study:

- Select: The work to be studied is selected. For instance, the study might be seeking to improve the productivity of a skidding operation.
- Record: This involves the recording of relevant facts about a job. Commonly used recording techniques include charts and diagrams to illustrate work process sequences or events of the selected study.
- Examine: At this stage, a questioning technique is used to critically examine the job. Primary questions are related to purpose (what), place (where), sequence (when), person (who) and means (how) of doing a job. Secondary questions follow to examine alternatives on each of the primary questions with a view to achieve improvement of work.
- Develop: Based on the questioning technique and understanding of driving factors of productivity (human, machine, socio-economics and environment), improved methods can be developed.
- Evaluate: The results attained by a new method are evaluated against work content in order to establish a standard time.
- Define: The new method is clearly spelt out in terms of process flow or events as well as expected amount of time to complete a job. Awareness initiatives aimed at informing workers about the new way of doing work are vital at this stage.
- Install: The code of practice is put in place. Training is a major prerequisite to back up installation and sustainability of a new method.
- Maintain: The results of a new code of practice are monitored and evaluated against the original code of practice. Continuous improvement takes cognisant of and makes necessary adjustments to a newly defined method.

2.5 Machine costing

Machine costs are classified as fixed, semi-variable or variable. Fixed costs are associated with owning of the machines while variable costs are the operating costs based on annual utilisation (Grobbelaar, 2000b). Fixed costs include the average annual interest for the depreciation period. According to Hogg *et al.* (2012) insurance, taxes, garaging and certificates form costs of owning. These annual costs are normally expressed as hourly costs.

Variable costs include costs of fuel and lubricants, auxiliary equipment and accessories (Grobbelaar, 2000b). Fuel consumption is determined based on engine nominal power and percentage of full rated engine power used during normal operation, "load factor". According to Malmberg (1989), lubricants are expressed as percentage of fuel consumption.

Semi-variable costs become fixed costs when machines are under-utilised and variable when fully utilised (Grobbelaar, 2000b). Examples of semi-variable costs include depreciation, repair costs and maintenance costs. The cost price and residual or salvage value are important in the calculation of depreciation. Machine costs are also based on useful life. Mellgren (1989) and Krieg (1999) indicated that the useful life in diesel engines is 10,000 machine hours. Notwithstanding this, most diesel engine forest machines have a useful life of 20,000 machine hours. Costs of auxiliary equipment and accessories are based on their own expected lifetime. The unit cost of a standard time (machine or man hours) is used to compile total costs (Jiao & Tseng, 1999).

2.6 Timber harvesting productivity models

Kammesheidt *et al*. (2001) stated that models represent reality of scenarios by using empirical data sets to predict long term situation dynamics. Over years, mathematical models used in forest harvesting have ranged from regression to complex stochastic and simulation process models (Wang & LeDoux, 2001). Feng *et al*. (2006) reported that regression models could be used to describe variables, predict estimates and relate observed and predicted estimates based on various statistical criteria. Some applications of regression models in timber harvesting have been reported by LeDoux (1985), Lortz *et al*. (1997) and Wang *et al*. (2004).

Regression modelling requires that key factors affecting the model are appropriately selected to be able to represent reality (Feng *et al*. 2006). Beal (2005) indicated that a common approach to determination of factors of significant influence in the model is stepwise regression analysis. In stepwise regression analysis, backward and/or forward selection of variables (factors) is used. As such, stepwise regression analyses have extensively been used to determine factors of significance in timber harvesting productivity modelling (Olsen *et al*., 1998; Ghaffarian & Sobhani, 2007; Behjou *et al*., 2008; Eker *et al*., 2011; Mousavi *et al*., 2012). Common stepwise selection criteria include (but not limited to) the residual mean squares, R^2, adjusted R^2 and Mallow's Cp to select or deselect candidate variables for application in the model (Kadane & Lazar, 2004; Feng *et al*., 2006) depending on the type of statistical package being used for analysis.

The residual mean square (RMS) is the quotient of residual sum of squares and residual degrees of freedom of analysis of variance (Gómez & Gómez, 1984:229). It is used in the calculation of t- and F-values which can be used in mean and variance separation between observed and fitted observations (Feng *et al*., 2006). As such, RMS is one of the important criteria for the determination of variables of significance in model subsets (Christensen, 2000). Notable applications of the RMS in timber harvesting modelling are recorded in Ghaffarian and Sobhani, (2007), Behjou *et al*. (2008) and Behjou *et al*. (2009).

The R^2 is a variance quotient derived from the regression sum of squares and total sum of squares (Bewick *et al*., 2003) also known as coefficient of determination. It is commonly used in timber harvesting stepwise regression to show the amount of variance explained by the model. However, it is closely related to the adjusted R^2. The adjusted R^2 is used in conjunction with Mallow's Cp (Cp statistic) to account for the contribution (variance) of each variable used in the model (Christensen, 2000). Hence, the best subsets of model variables are determined when the value of Cp approaches p = number of (including intercept) variables present in model (SASII, 2010).

Where the specific influence of a variable (factor) in the model requires to be known, the use of adjusted R^2 and Cp statistic becomes relevant (personal communication by M. Smith, 15 March 2012, Featherwood Estate, Pretoria). Therefore, these criteria are deemed appropriate for stepwise selection of factors of timber harvesting productivity and model building for the Viphya study.

In a model building process, it is not uncommon to partition the data sets into randomly distributed training, test and validation sets (Feng *et al*., 2006). A training data set serves to build the model while its accuracy is determined on the test set. Validation determines the reliability of the model to relate reasonably well with predictor variables under comparable environments (Halfon, 1989). Feng *et al*. (2006) indicated that about 30% of the data may be withheld for validation while the remainder may be retained for training and testing the model. Notwithstanding this, partitioning may somehow depend on the amounts of sampled data sets. Therefore, other dimensions of validation require that a model is built based on a bigger portion, tested on the smaller (remaining) portion and validated on whole data sets (personal communication by M. Smith, 16 March 2012, Featherwood Estate, Pretoria). For meaningful statistical inferences of this study, the latter approach was particularly appropriate.

Widely used statistical validation tests in forest biometrics include paired t-test, the chi-square test, F-test and the regression test for observed and predicted parametric data sets (Yang *et al*., 2004; Spinelli *et al*., 2009). Most of these tests hypothesise that the mean difference between observed and predicted variables is zero. In other instances, the test for observed and predicted data uses a regression line between dependent (observed) and independent (predicted) variables to determine correlation. In spite of different hypothesis formulations, statistical validation tests compare the margin of error between observed and predicted variables (Yang *et al*., 2004). The practical outcome of these different validation methods is virtually the same.

CHAPTER 3: METHODOLOGY

This chapter contains the general methodology (materials and methods) of this study. Key aspects highlighted include description of the study site, materials used, methods used and analysis of time study and forest inventory data. The methods involving synthetic data for simulation of mechanised harvesting systems are also presented.

3.1 Description of the study site

The Viphya forest plantations stretch between latitudes 11° S and 12° S and longitudes 33° 45' E and 34° 10' E in northern Malawi. The area receives a mean annual rainfall between 750 mm and 1560 mm with an overall average of 1200 mm per annum. Rainfall is at its peak during the summer months of January and March, although showers and mist continue during the dry season, from June to October. The minimum daily temperatures are 10°C in winter. Maximum daily temperatures are about 28°C in November. The mean annual temperature for the study area is about 19°C (VPD, 2005).

The terrain is undulating with slopes varying from flat to very steep. Soils are reddish in colour with proportions of silt, clay, loam or silt-clay with pronounced quartz material in some ridges. Generally, these soils become highly plastic during the rainy season. In valley bottoms, clayey poorly drained soils are common in the Viphya (Cornelius, 1989).

The study was conducted in *Pinus kesiya* stands in the Viphya forest plantations in compartments 252B and 253C of Kalungulu forest planted in 1977 and 151B of Champhoyo forest planted in 1975 (Fig. 3.1). The choice of compartments for this study followed a harvesting plan designed by Raiply to undertake clear-felling for its plymill, fibreboard mill and sawmill. *Pinus kesiya* is regarded as an alternative prime wood after *P. elliottii* (which has currently drastically dwindled) especially for the plywood production.

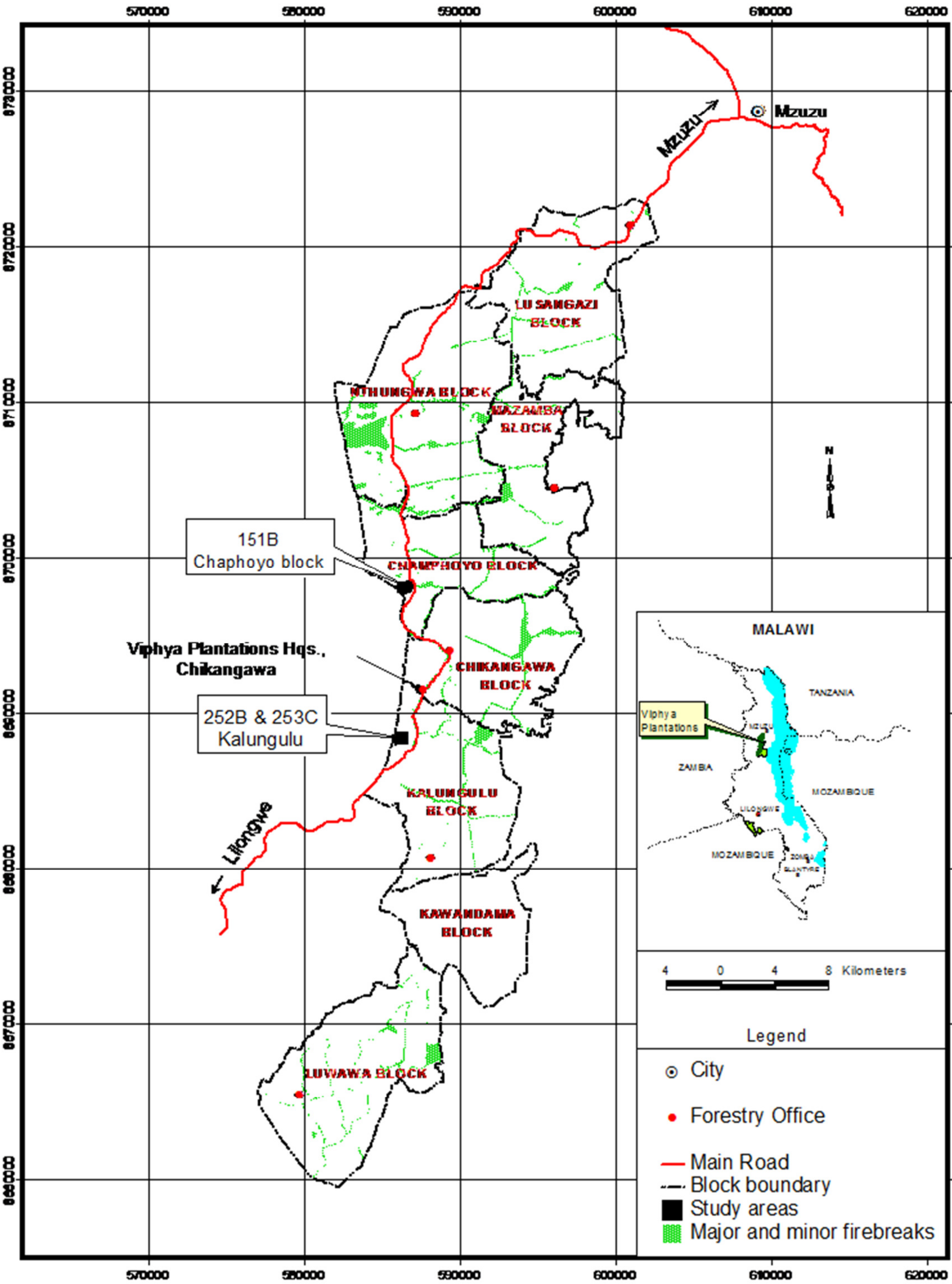

Fig. 3. 1. Map of the Viphya forest plantations showing compartments C252B and C253C (Kalungulu) and Z151B (Champhoyo)

3.1.1 Stand characteristics

Stand density of *P. kesiya* in the study sites was estimated to be 375-450 stems per hectare (SPH) following sanitary thinning that took place in early 1990's especially in Kalungulu forest (VPD, 2005). Although slopes ranged from 5 to 25% in the study sites, the Viphya forest plantations are characterised by variably higher slope grades (>35%) to the eastern side. The ground conditions encountered were very good, good and moderate only. Moderate ground conditions were particularly experienced in Z151B due to winter rains. The maximum ground roughness was "uneven" in all compartments. Table 3.1 presents the stand characteristics of the study compartments.

Table 3. 1. Stand information of the study sites

Compartment	Total area (ha)	SPH	Mean Dbh (cm)	Mean Height (m)	Slope (%)	Ground condition	Ground roughness	Brush density (Visibility)
C252B	14.5	375	41.2	27.08	8-15	Very good	Slightly Uneven	>8 m
C253C	9.2	375	41.2	27.08	5-17	Very good	Smooth to Uneven	>8 m
Z151B	70.0*	450	38.6	29.40	15-25	Very good to Moderate	Slightly Uneven to Uneven	>8 m

* Only about 2 ha were observed for work studies.

3.1.2 Timber harvesting system description

The study was carried out on a full-tree timber harvesting method. Chainsaw felling operations were confined to stem severing. Debranching and cross-cutting were not part of the operations under study. Similarly, the simulated feller buncher system excluded these two operations as they formed part of the roadside landing (downstream) operations.

The choice of a tracked self-levelling feller buncher to undertake simulated mechanised felling was not solely based on stand characteristics presented in Table 3.1 but rather on wider plantations site characteristics. The tracked feller buncher has capability to work across a wider range of terrain classes that may exist on the Viphya forest plantations.

The operations of a grapple skidder were observed from point of origin (landing), to compartment and back to landing. The simulated feller buncher and grapple skidder system accommodated the pre-bunching operation of felled full-trees. Table 3.2 illustrates the systems design for full-tree method at Viphya forest plantations.

Table 3. 2. Systems design for full-tree harvesting method at Viphya forest plantations

System	Locality			Operation
	Stand	Skid trail	Roadside landing	
Chainsaw - Husqvarna 372XP				Motor-manual felling
Self-levelling Feller buncher - JD759JH				Mechanised felling and pre-bunching
Grapple Skidder - CAT 525C		⟺		Extraction

3.2 Research design and sample size

The research followed a work study approach (Fig 3.2). Dotted and solid arrows represent independent work studies for a grapple skidder and a chainsaw operation, respectively. The thick arrow in the middle represents progression from initial work study to productivity. Time study and forest measurement techniques were used to quantify productivity of felling and skidding machines. Felling and skidding tasks were each sub-divided into distinctive cycle elements.

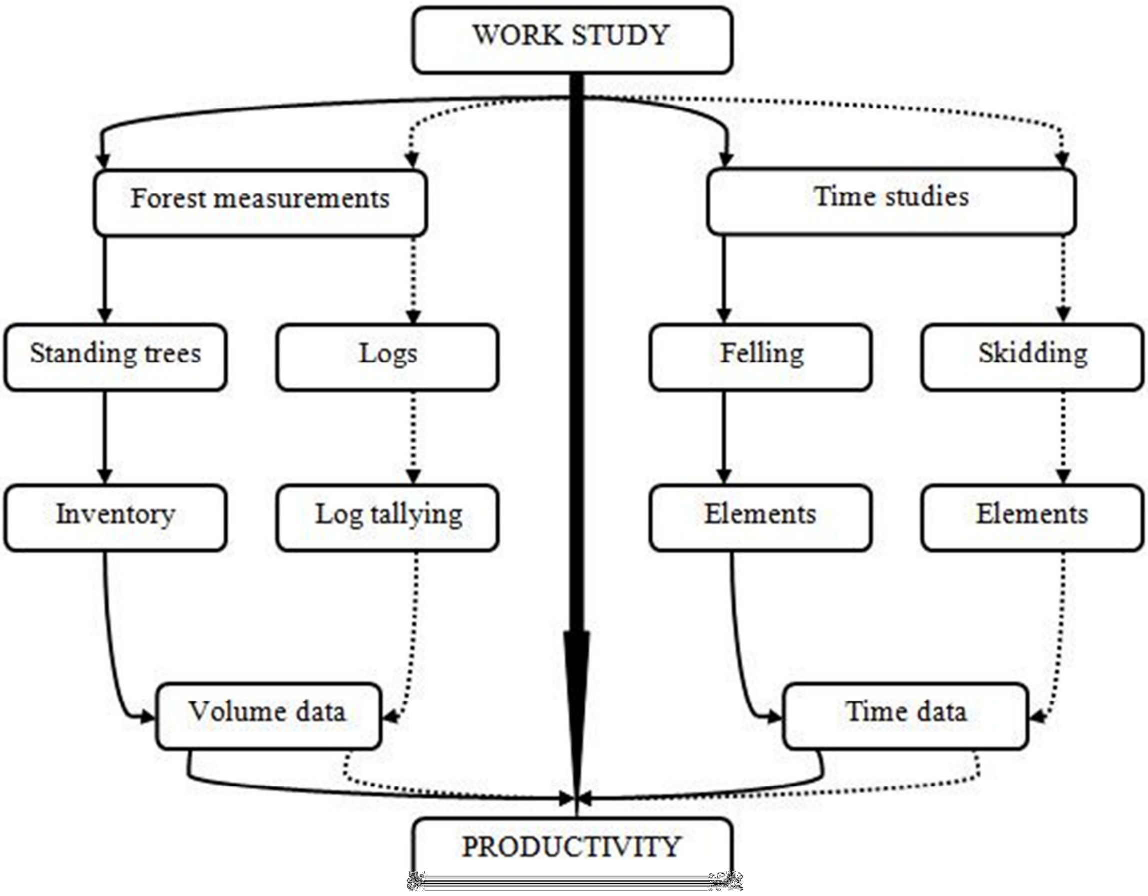

Fig. 3. 2. Schematic design of timber harvesting work study

The elements for chainsaw felling comprised file, fuel, walk to tree, cut and delay in a full-tree harvesting method while those for skidding were drive empty, change position, bunch, drive loaded and drop, turn, align and delay. Break points of felling and skidding elements are provided in Appendix 1. Corresponding forest measurements were conducted for standing trees and logs to determine felled and skidded volume.

The minimum number of cycles assessed in each work study was determined using a statistical method (Appendices 2 & 3) and Equation 2.9. As such, 349 felling cycles and 412 skidding cycles were observed during the entire period of study. For standing tree assessments, at least 30 trees were sampled per compartment for height and diameter measurements. All incoming logs per skidding cycle were measured at the landing. Trees to be felled or skidded were randomly selected by the operators with regard to ease of operation and safety aspects.

3.3 Data collection and methods

In this section, primary and secondary data sources are described. Time study, forest inventory and simulation procedures are presented.

3.3.1 Primary data: work study

In felling and skidding time studies, elemental times were measured in centi-minutes using a digital decimal stopwatch. Total cycle time for each operation was calculated as the sum of elemental times (Appendices 4 & 5). In felling, each severed tree constituted a cycle while in skidding, the number of felled trees extracted to the roadside (landing) per trip was recorded.

For standing trees, six square plots of 400 m^2 sizes were made to facilitate volume determination per plot. All standing trees were assessed for diameter at breast height (dbh) in centimetres in each plot. A caliper was used to measure stem diameters. Diameter-height pair sample trees consisted of all trees in each plot. A Suunto clinometer was used to assess heights of standing trees; and linear distance between a tree and point of measure was measured with a 50 m tape. Local volume tables based on Schumacher and Hall's model (Equation 2.3) were used to determine plot and compartment volume.

Log diameters were measured on the thick-end, middle and thin-end in centimetres. Log length was measured in metres using a linear tape. Extraction distance (compartment to landing) was measured in metres using a GPS. Other site-based information applicable to felling and skidding operations included slope (measured in percentage), ground condition, ground roughness and brush density recorded as ordinal data (Table 3.3). Relative soil moisture content was to qualify ground conditions; obstacle height and incident for ground roughness and visibility for brush density. Log volume was estimated using Newton's model (Equation 2.7).

Table 3. 3. Other site-based factors and associated dummy variables

Factor	Explanation	Ordinal	Dummy
Ground condition	Very good	1	-2*
	Good	2	-1
	Moderate	3	0
	Poor	4	1
	Very poor	5	2
Ground roughness	Smooth	1	-2*
	Slightly uneven	2	-1
	Uneven	3	0
	Rough	4	1
	Very rough	5	2
Brush density	Very good visibility +10 m	1	-2*
	Good visibility +8 m	2	-1
	Restricted visibility +6 m	3	0
	Poor visibility +4 m	4	1
	Extremely poor visibility +2 m	5	2

*Reference dummies for parameters of factors

In order to estimate volume under-bark from diameter over-bark, bark factors or bark thickness models were required for both standing trees as well as logs (Cao & Pepper, 1986). Since the bark thickness models for *P. kesiya* were unavailable, diameter over-bark and diameter under-bark subsamples were drawn from the population to enable the development of an appropriate bark thickness model (see Appendix 6) as described by Avery and Burkhart (2002).

3.3.2 Secondary data: simulation

Apart from field observations (Fig. 3.2), secondary data sources were also used for simulation purposes of productivity of a feller buncher (mechanised system) in place of a chainsaw (motor-manual system). Typical work elements for a feller buncher comprise:

a) Move to position: feller buncher takes position and draws processor head down the tree;
b) Cut: arms hold tree, saw is operated and machine intends to move away;
c) Swing tree to bunch: machine moves with cut tree to the next target or bunch;
d) Swing to next tree: processor head advances next tree and draws down;
e) Delays: personal, operational or mechanical in nature,

as defined by Thomson (2003), Wang and LeDoux (2003) and Acuna *et al*. (2011).

Stand variable points (ranks) for feller buncher (Table 3.4), were summarised to simulate observed site data for Viphya in Table 3.5. Similarly, stand variable points for CAT 525C grapple skidder (Table 3.6), were summarised to simulate observed skidding site data in Table 3.7. Synthetic data for mechanised systems (feller buncher and grapple skidder combinations) were used because of absence of such systems in the study area.

Table 3. 4. Variable points for a feller buncher

Stand characteristics	Variable	Points
Average tree volume	0.80 m^3	0
	1.00 m^3	1
	1.20 m^3	2
	1.40 m^3	3
	1.60 m^3	4
Slope	0-10%	0
	11-20%	1
	21-25%	2
	25-35%	3
	+35%	5
Bush density	Good visibility +10 m	0
	Restricted visibility + 5 m	4
	Poor visibility + 2 m	6
Ground condition	Good	0
	Moderate (wet, loose)	1
	Poor (unstable)	2
	Very poor (very unstable)	4
Ground roughness	Smooth	0
	Slightly uneven	1
	Uneven	2
	Rough	3
	Very rough (rocky)	5

Source: FS (2007).

Table 3. 5. Summarised feller buncher variable-points for Viphya

Average stand characteristics	Variable	Points
Volume per log	1.45 m^3	3.5
Slope	11.5%	1
Brush density	+9.5 m	0.4
Ground condition	Very good	0
Ground roughness	Slightly uneven	1
Cumulative		5.9

Table 3. 6. Variable points for a grapple skidder CAT 525C

Stand characteristics	Variable	Points
Average tree volume	> 0.60 m^3	0
	0.40-0.60 m^3	1
	< 0.40 m^3	3
Average lead distance	0-150 m	0
	151-200 m	1
	201-250 m	2
	251-300 m	3
	301-400 m	4
	401-500 m	6
Slope	0-7% up or down	0
	7-11% up	2
	7-11% down	0
	11-20% up	4
	11-20% down	2
	20-29% up	8
	20-29% down	4
	30-35% down (exceptional)	6
Ground condition	Good	0
	Moderate (wet, loose)	2
	Poor (unstable)	3
	Very poor (very unstable)	4
Ground roughness	Smooth	0
	Slightly uneven	1
	Uneven	2
	Rough	3
	Very rough (rocky)	4
Chainsaw felling	No bunching of timber	5
Roadside skidding	> 75 m	1

Source: FS (2007).

Table 3. 7. Summarised skidding variable-points for Viphya

Average stand characteristics	Variable	Points
Volume per log	1.45 m^3	0
Lead (skid) distance	134 m	0
Slope	11.5%	3
Ground condition	Very good	0
Ground roughness	Slightly uneven	1
Roadside skidding	>75 m	1
Cumulative		5

The cumulative points for average stand characteristics in a feller buncher operation (Table 3.5) and skidder operation (Table 3.7) were correspondingly and proportionately used to estimate production rates in Table 3.8 for feller buncher and Table 3.9 for grapple skidder.

For instance, if the cumulative variable points equalled 14 (in Table 3.5) then the production rate would be 50 tree/hr or 73 m^3/hr (in Table 3.8) at an average tree volume of 1.45 m^3, similarly in Table 3.7 and Table 3.9.

Table 3. 8. Feller buncher production standards for pines

Productivity	Cumulative points											
	0	1	2	3	4	5	**6**	8	10	12	14	16
Trees/hour	110	105	100	95	90	85	**80**	70	63	56	50	44
m^3/hour*	160	152	145	138	131	123	**116**	102	91	81	73	64

*Average tree volume of 1.45 m^3

Source: FS (2007).

Table 3. 9. Production standards for a Grapple Skidder CAT 525C

Productivity	Cumulative points												
	0	1	3	**5**	7	9	11	13	15	17	19	21	23
Cycles/hr	20	18	16	**15**	14	13	12	11	10	9	8	7	6
m^3/hour	80	72	64	**60**	56	52	48	44	40	36	32	28	24
m^3/hour*	100	90	80	**75**	70	65	60	55	50	45	40	35	30

*Based on 5 m^3/cycle

Source: FS (2007).

Fixed, variable, labour and overhead costs (in USD equivalent) of the harvesting machines were recorded for calculation of hourly production costs. Present cost values and exchange rates were applied.

3.4 Data analysis

Subsequent sections contain procedures followed to analyse the data. The assumptions for regressions are tested, the model building process for selection of suitable factors, and simulation analysis of mechanised systems based on local factors are presented.

3.4.1 Normality tests

Multiple regressions were used to analyse the delay-free felling and skidding productivity data (Appendix 7 and Appendix 8, respectively). In determining felling productivity, the dependent variable was felling time and independent variables were dbh, distance between trees, slope, brush density, ground condition and ground roughness. Filing and fuelling elements were excluded in modelling because of high residual values. These elements are practically expressed as percentages of the total felling time (personal communication by B. Shuttleworth, 12 June 2012, Forestry Solutions Pty, South Africa). For skidding time, potential independent variables were distance, distance squared, slope, ground condition, ground roughness and total volume per cycle. A quadratic transformation for distance was carried out in order to improve the model fit and reduce the error variance. Ground condition, ground roughness and brush density were treated as ordinal dummy variables in the model (Table 3.3). Normality diagnostic tests were conducted on felling and skidding data (O'Neill, 2010) using SAS 9.2.

These data sets failed to satisfy the assumptions for regression analyses, as such, box-cox transformations were carried out in each case on independent variables to identify appropriate types of transformation for the dependent variable (Box & Cox, 1964). Logarithmic to the base e (ln) transformation was identified and conducted for felling data while square root (sqrt) transformation was identified and conducted for the skidding model. Transformations returned normal distributions for felling (Appendix 7) and for skidding data (Appendix 8).

3.4.2 Factor selection and model building

Stepwise multiple regression analyses were used to determine factors of significance on felling and skidding times using backward elimination and forward inclusion to select or deselect factors. Prior to the selection of factors, data were randomised using a 'Rand function' in MS Excel to increase independence. Data were then partitioned into training, test and validation sets, i.e. 70%, 30% and 100%, respectively. Factors were selected from training and scored with adjusted R^2, Mallow's Cp and F-probability criteria. Regression estimates for felling time and skidding time were developed from respective selected factors using training set in GenStat Discovery Edition 4.

The performance of the models was tested and validated using test (30%) and validation (100%) data sets. A validation test of the model was conducted by regressing dependent (observed) on dependent (predicted) variables for training, test and validation data (Halfon, 1989) using GenStat Discovery Edition 4.

Further diagnostic (post-hoc) correlation analyses were conducted to test the relatedness of ground roughness and ground condition on predicted square root of cycle time. The objective of this analysis was to separate relatedness of the factors influencing the model. A correlation coefficient (R) was used to determine the relationship between the ground condition and roughness.

3.4.3 Productivity analysis

Costing models were used to determine the production rates and costs based on average output per machine hour for observed (chainsaw-grapple skidder) and simulated (feller buncher-grapple skidder) productivities. The costing analyses for chainsaw, grapple skidder (unbunched), simulated feller buncher and simulated grapple skidder (pre-bunched) were based on a full-tree method of harvesting.

CHAPTER 4: RESULTS

This chapter outlines results of site-based factors affecting chainsaw felling time; estimates for total felling time and the amount of variation accounted for by the model and the validity of the selected factors to predict felling time. The results for grapple skidder cycle time models are presented based on prevailing site-factors. The production rates and costs of mechanised systems are also simulated based on the observed semi-mechanised timber harvesting systems.

4.1 Factors affecting felling time

Six site-based factors were considered as having an effect on the cycle time of a chainsaw. These were: (1) Diameter at breast height (dbh); (2) Distance; (3) Slope; (4) Ground condition; (5) Brush density and (6) Ground roughness. Table 4.1 shows the selection of factors affecting cycle time of a chainsaw using the training data set. The probabilities shown in the subsets are based on F-statistics, i.e. on variance ratios.

In a subset with six factors, the results showed that tree size (dbh) and distance between trees had significant ($P < 0.01$) influence on tree felling cycle time. However, slope, ground condition, brush density and ground roughness were insignificant at $P = 0.05$. Notably, ground roughness was consistently insignificant ($P > 0.05$) in all subsets. In a subset with one factor, dbh contributed 53.88%, inter-tree distance contributed 4.21%, slope accounted for 3.08%, ground condition accounted for 1.78%, brush density contributed 3.35% and ground roughness contributed <0.00% of the variation. The highest adj. R^2 of 56.61% and Cp = 4.34 were attained when dbh, distance, slope and brush density (subset with four factors) were present in the model, although slope and brush density were not significant at $P = 0.05$. Test and validation data sets also showed similar trends in Appendix 9 and Appendix 10, respectively.

Table 4. 1. Stepwise selection of the best subset of site-based factors affecting felling time using training data set

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
53.88	15.43	2	.000	-	-	-	-	-
4.21	290.50	2	-	.001	-	-	-	-
3.35	295.06	3	-	-	-	-	.006	-
3.08	296.74	2	-	-	.003	-	-	-
1.78	303.92	2	-	-	-	.021	-	-
<0.00	316.05	2	-	-	-	-	-	.899

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.30	3.00	3	.000	.000	-	-	-	-
54.87	10.90	3	.000	-	.013	-	-	-
54.81	11.22	3	.000	-	-	.015	-	-
54.22	15.43	4	.000	-	-	-	.150	-
53.73	17.16	3	.000	-	-	-	-	.614
6.86	275.53	4	-	.002	-	-	.013	-
5.61	282.57	3	-	.007	.033	-	-	-
4.85	286.61	4	-	-	-	.029	.008	-

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.59	2.41	4	.000	.001	.108	-	-	-
56.45	3.18	4	.000	.002	-	.177	-	-
56.40	4.45	5	.000	.000	-	-	.280	-
56.15	4.84	4	.000	.000	-	-	-	.689
55.02	12.03	5	.000	-	-	.023	.214	-
54.89	12.71	5	.000	-	.034	-	.349	-
54.85	11.96	4	.000	-	.270	.342	-	-
54.71	12.72	4	.000	-	.013	-	-	.684

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.61	**4.34**	**6**	**.000**	**.001**	**.146**	**-**	**.353**	**-**
56.60	4.36	6	.000	.002	-	.148	.245	-
56.43	4.29	5	.000	.002	.347	.728	-	-
56.43	4.29	5	.000	.001	.111	-	-	.728
56.28	5.10	5	.000	.002	-	.188	-	.784
56.25	6.30	6	.000	.000	-	-	.282	.695
54.88	13.73	6	.000	-	.593	.330	.341	-
54.83	14.03	6	.000	-	-	.031	.223	.994

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.47	6.09	7	.000	.002	.602	.619	.333	-
56.45	6.19	7	.000	.001	.147	-	.349	.696
56.42	6.36	7	.000	.002	-	.165	.255	.974
56.27	6.19	6	.000	.002	.342	.753	-	.753
54.71	15.66	7	.000	-	.551	.365	.347	.789
6.65	276.29	7	-	.008	.720	.482	.038	.535

Best subsets with 6 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.30	8.00	8	.000	.002	.548	.666	.335	.761

4.1.1 Prediction estimates for felling

The results of tree felling cycle time prediction estimates are based on the training set (Table 4.1). Table 4.2 shows that the constant, diameter at breast height and distance between trees are highly significant (P <0.01) in the felling time model. The estimate of dbh was 0.03005 ± 0.00177 and the coefficient for distance between trees was 0.02291 ± 0.00603. The adj. R^2 of the model was 56.3 ± 0.251%.

Table 4. 2. Predictor variable estimates on felling time using training data

Set	Parameter	estimate	s.e.c.	t(278)	t pr.	adj. R^2	s.e.r.
	Constant	-1.2443	0.0717	-17.35	<0.001	56.3	0.251
Train	Dbh	0.03005	0.00177	17.01	<0.001		
	Distance	0.02291	0.00603	3.80	<0.001		

Based on Table 4.2, a generic mathematical model is presented as in Equation 4.1 and a specific model developed is shown in Equation 4.2.

$$\ln(f) = b_0 + b_1 Dbh + b_2 Distance \quad \text{(Equation 4.1)}$$

where;

f = Felling time in minutes

$b_0 =$ Constant coefficient

$b_1, b_2 =$ Parameter coefficients

$$\ln(f) = -1.2443 + 0.03005. Dbh + 0.03632. Distance \quad \text{(Equation 4.2)}$$

$$adj. R^2 = 56.3\%$$

$$s.e.r. = 0.251$$

Note: 11.4% of total delay-free felling time is lost to filing and fuelling. Therefore actual felling time (including filing and fuelling) is multiplied by a factor of 1.114.

4.1.2 Felling model validation

The prediction model (Equation 4.2) was tested for validity using test and validation data sets. Fig. 3.3 shows the graphical contrast between observed and predicted felling times on a validation set. The fit for observed and predicted data set is about 50% (50:50) for each data set.

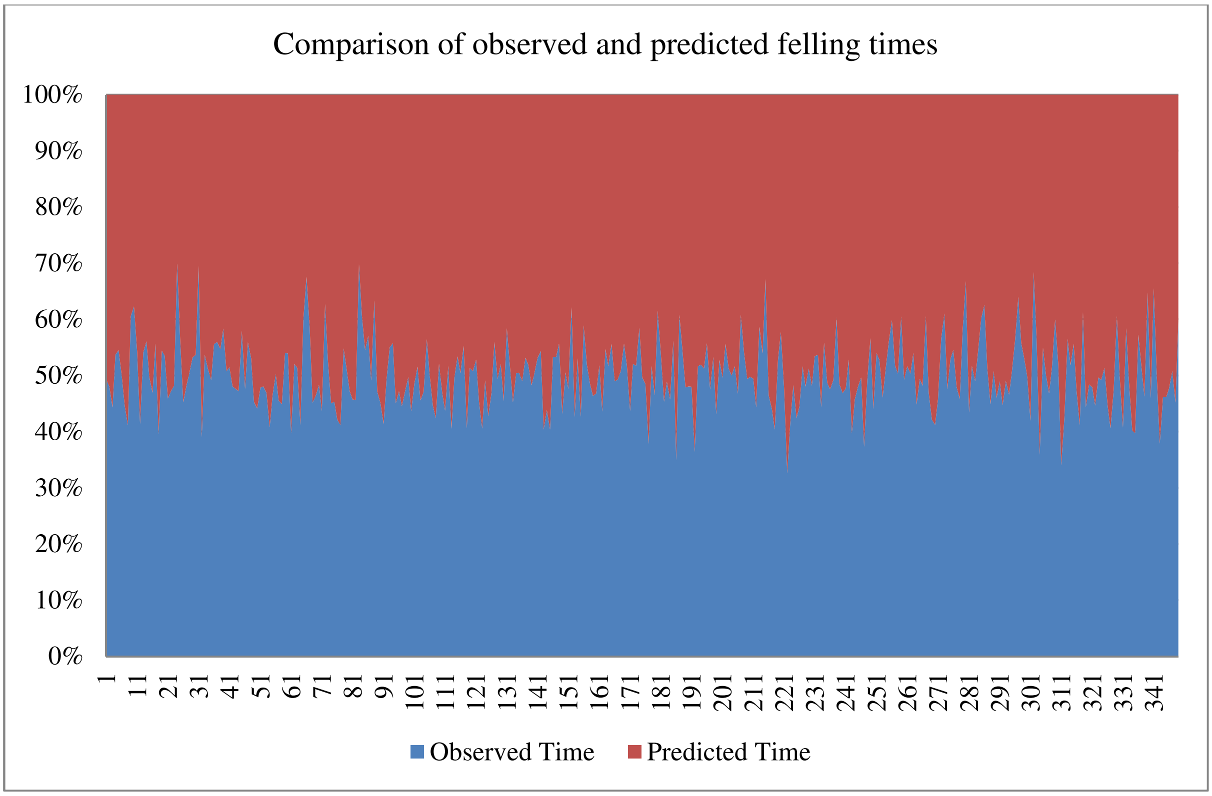

Fig. 4. 1. A mirror-image of observed and fitted felling times

The statistical test for validation (Table 4.3) shows the estimates for α (constant) and β (slope) of observed over predicted felling time i.e. $(\text{observed f} = \alpha + \beta.\text{predicted f})$ in which observed f_1 = training set, observed f_2 = testing set and observed f_3 = validation data set. In the test data set, the constant was 0.0237, slope was 1.220 and adj. R^2 was 56.2%. In the validation set, the constant was 0.0079, slope was 1.0586 and adj. R^2 was 56.1%.

Table 4. 3. Validation of observed and predicted natural log felling times

	α	β	adj. R^2	Sample size
Observed f_1	0.0001^{ns}	1.0001	56.5%	244
Observed f_2	0.0237^{ns}	1.2200	56.2%	105
Observed f_3	0.0079^{ns}	1.0586	56.1%	349

^{ns} denotes insignificant (P >0.05).

4.2 Factors affecting skidding time

In this study, potential factors affecting skidding time were (1) Distance; (2) Distance squared; (3) Volume per cycle; (4) Slope; (5) Ground condition and (6) Ground roughness. Table 4.4 shows the selection of factors affecting skidding cycle time using the training set. The probability values shown in the subsets are based on F-statistics.

In a subset with six factors, the effects of distance, distance squared, volume per cycle, slope and ground condition, were significant at P = 0.05 with an associated adj. R^2 of 61.94%; Cp = 9.0. In this subset, ground roughness was insignificant (P >0.05). In a subset with one factor, distance accounted for 51.01%, distance squared = 42.17%, ground roughness = 16.39%, ground condition = 6.73%, volume per cycle = 5.98% and slope = 3.82% of variation (P = <0.001). The highest account of variation (adj. R^2 = 62.01; Cp = 6.49) was explained by distance, distance squared, volume per cycle, slope and ground condition in a subset with five factors. Notwithstanding, these results differed from those found in the test and validation data sets. The test set yielded its highest adj. R^2 = 60.92%; Cp = 6.79 with distance, distance squared, volume per cycle, slope and ground roughness where slope was insignificant (P >0.05) (Appendix 11). In the validation set, all six factors were significant at P = 0.05 (Appendix 12).

Table 4. 4. Stepwise selection of the best subset of site-based factors affecting skidding time using training data set

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
51.01	84.15	2	.000	-	-	-	-	-
42.17	150.60	2	-	.000	-	-	-	-
16.39	344.08	3	-	-	-	-	-	.000
6.73	416.42	3	-	-	-	-	.000	-
5.98	422.50	2	-	-	.000	-	-	-
3.82	438.75	2	-	-	-	.000	-	-

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
54.77	56.66	3	.000	.000	-	-	-	-
53.61	65.35	3	.000	-	.000	-	-	-
53.40	66.94	3	.000	-	-	.000	-	-
53.13	69.75	4	.000	-	-	-	.001	-
52.83	71.99	4	.000	-	-	-	-	.002
45.47	126.37	3	-	.000	-	.000	-	-
45.39	127.49	4	-	.000	-	-	-	.000
45.39	127.53	4	-	.000	-	-	.000	-

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
58.20	31.95	4	.000	.000	.000	-	-	-
57.43	37.62	4	.000	-	.000	.000	-	-
56.98	41.89	5	.000	-	.000	-	.000	-
56.41	46.09	5	.000	-	.000	-	-	.000
56.37	45.55	4	.000	.000	-	.001	-	-
56.19	47.73	5	.000	.000	-	-	-	.004
56.16	48.02	5	.000	.000	-	-	.005	-
53.99	64.13	5	.000	-	-	.013	.062	-

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
61.05	11.63	5	.000	.000	.000	.000	-	-
60.67	15.40	6	.000	.000	.000	-	.000	-
60.54	16.36	6	.000	.000	.000	-	-	.000
58.73	29.78	6	.000	-	.000	.000	.005	-
57.62	37.99	6	.000	-	.000	.003	-	.197
57.40	40.52	7	.000	-	.000	-	.015	.093
56.71	44.79	6	.000	.000	-	.033	.125	-
56.50	46.29	6	.000	.000	-	.084	-	.242

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
62.01	**6.49**	**7**	**.000**	**.000**	**.000**	**.001**	**.011**	**-**
61.30	11.73	7	.000	.000	.000	.011	-	.149
61.14	13.89	8	.000	.000	.000	-	.044	.069
58.58	32.76	8	.000	-	.000	.003	.015	.624
56.66	46.83	8	.000	.000	-	.119	.221	.424
51.25	86.65	8	-	.000	.000	.007	.016	.297

Best subsets with 6 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
61.94	9.00	9	.000	.000	.000	.009	.036	.476

Note: Correlation analysis results for ground condition and ground roughness are presented in Appendix 13.

4.2.1 Prediction estimates for skidding

Table 4.5 shows variable estimates in a skidding time model. The model estimates were significantly ($P < 0.01$) influenced by the constant, distance, distance squared, volumes per cycle, slope and moderate ground conditions. Good ground conditions were insignificant ($P > 0.05$) in the model. Constant had a coefficient value of 1.395 with a standard error of coefficient (s.e.c.) of 0.161 when very good ground conditions were used. The coefficient for moderate ground conditions was 0.414 ± 0.143 whilst volume per cycle was estimated at 0.1110 ± 0.0175. The adj. R^2 of the model was 62.0% with a standard error of 0.413.

Table 4. 5. Predictor variable estimates on skidding time using training data

Parameter	estimate	s.e.c.	t(281)	t pr.
Constant (b_0)	1.395	0.161	8.66	<0.001
Distance (x_1)	0.01702	0.00189	9.02	<0.001
Distance quadratic (x_2)	-0.00003524	0.000007	-5.03	<0.001
Volume per cycle (x_3)	0.1110	0.0175	6.35	<0.001
Slope (x_4)	0.01882	0.00569	3.31	0.001
Ground condition - Good (D_2)	-0.022	0.131	-0.16	0.869
Ground condition - Moderate (D_3)	0.414	0.143	2.89	0.004
adj. R^2 = 62.0% (0.413)				

Parameters for factors are differences compared with the reference level: i.e. for a ground condition factor, its reference level is very good (D_1). Values in the parenthesis denote standard error of regression (s.e.r.).

Mathematically, Table 4.5 can be presented generically as in Equation 4.3 and specifically in Equations 4.4 when a reference dummy, "very good," is used. When ground conditions are "good" and "moderate", Equation 4.5 and Equation 4.6 are respectively applicable.

$$\text{sqrt}(y) = b_0 + b_1x_1 + b_2{x_2}^2 + b_3x_3 + b_4x_4 + d_iD_i \qquad \text{(Equation 4.3)}$$

Where;

$y =$ Predicted skidding time in standard minutes

$x_1 =$ Distance from stump area to landing in metres

$x_2 =$ Distance (square transformation)

$x_3 =$ Volume per cycle in m^3 per cycle

$x_4 =$ Slope in percent

$D_i =$ Dummy variables for ground condition for i = good and moderate

$b_0 =$ Constant coefficient

$b_1, b_2, b_3, b_4 =$ Parameter coefficients

$d_i =$ Dummy variable coefficients for ground condition for i = good and moderate

$$\text{sqrt}(y_{11}) = 1.395 + 0.01702x_1 - 0.00003524{x_2}^2 + 0.111x_3 + 0.01882x_4$$

(Equation 4.4

$$\text{sqrt}(y_{12}) = 1.373 + 0.01702x_1 - 0.00003524{x_2}^2 + 0.111x_3 + 0.01882x_4$$

(Equation 4.5)

$$\text{sqrt}(y_{13}) = 1.809 + 0.01702x_1 - 0.00003524{x_2}^2 + 0.111x_3 + 0.01882x_4$$

(Equation 4.6)

Where;

$y_{11} =$ Predicted skidding time in minutes for very good ground condition

$y_{12} =$ Predicted skidding time in minutes for good ground condition

$y_{13} =$ Predicted skidding time in minutes for moderate ground condition

Other notation as is in (Equation 4.3).

4.2.2 Skidding model validation

The usefulness of Equation 4.4 was tested for validity using graphical and statistical analyses. Fig. 4.2 is a mirror image between the observed and predicted skidding times using the validation data set which showed a match of 50% (i.e. 50:50) of each data set.

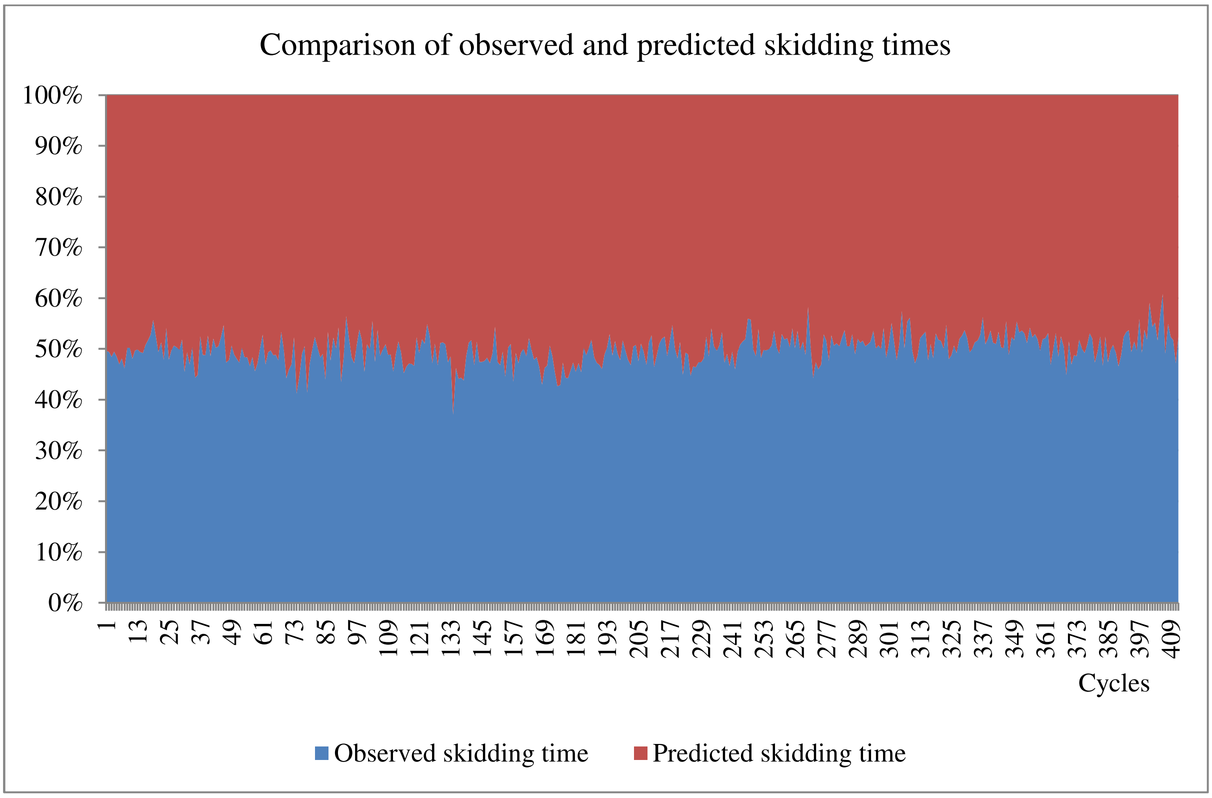

Fig. 4. 2. A mirror-image of observed and fitted skidding times

Estimates for α (constant) and β (slope) in a model of observed $y = \alpha + \beta.(\text{predicted } y)$ are shown in a statistical validation test (Table 4.6) based on Equation 4.4. Observed y_1 = training set, observed y_2 = testing set and observed y_3 = validation data set. In the test data set, the constant was -0.030, slope is 1.0116 and adj. R^2 is 61.4%. In the validation set, α was -0.126, slope was 1.0383 and adj. R^2 was 60.5%.

Table 4. 6. Validation of observed and predicted square root transformed skidding times

	α	β	adj. R^2	Sample size
Observed y_1	-0.030^{ns}	1.0116	61.4%	288
Observed y_2	-0.370^{ns}	1.1060	58.8%	124
Observed y_3	-0.126^{ns}	1.0383	60.5%	412

^{ns} denotes insignificant (P >0.05).

4.3 Production rates and costs for semi-mechanised and mechanised systems

Table 4.7 shows the production rates and costs of a semi-mechanised harvesting system that had an annual target of 200,000 m^3 of logs (Appendix 14.1 & Appendix 14.2) in the Viphya forest plantations. To achieve the target, the system required 3 chainsaws and 6 grapple skidders. The production rate for a chainsaw was 71.08 m^3 per machine hour (m^3/pmh) at a cost of $0.27 per cubic metre. The observed productivity for a grapple skidder averaged 21.51 m^3 per machine hour at a production cost of $4.63 per m^3. The combined operational cost for the semi-mechanised system was $4.90 per m^3 at $118.78 per machine hour. Two people (operator and assistant) were required per machine for any particular production phase.

Table 4. 7. Production rates and costs for a semi-mechanised system

System	Locality			Production requirements			Productivity		
	Stand	Trail	Roadside landing	Annual target (m^3)	No. of machines	No. of workers	Cost ($/$m^3$)	Rate (m^3/pmh)	Cost ($/pmh)
Chainsaw - Husqvarna 372XP				200 000	3	6	0.27	71.08	19.19
Grapple Skidder - CAT 525C				200 000	6	12	4.63	21.51	99.59
Total (excluding overheads)				-	9	18	4.90	-	118.78

The simulated mechanised system is shown in Table 4.8. When a feller buncher was used in place of a chainsaw in similar stand and site characteristics (Table 3.4 & Table 3.6); and same number of working days and shift, 2 felling machines and 2 skidding machines were required to produce 200,000 m^3 per annum (Appendix 15.1 and Appendix 15.2). A production cost of $286.52 per machine-hour was associated with a volume production of 116.0 m^3 per hour. The production rate of a grapple skidder increased to 75.0 m^3 per machine-hour at a cost of $1.54 per cubic metre. The total cost for mechanised system was $4.01 per m^3 and each machine required one operator.

Table 4. 8. Simulated production rates and costs for a mechanised system

System	Locality			Production requirements			Productivity		
	Stand	Trail	Roadside landing	Annual target (m^3)	No. of machines	No. of workers	Cost ($\$/m^3$)	Rate (m^3/pmh)	Cost ($/pmh)
Self-levelling Feller buncher - JD759JH				200 000	2	2	2.47	116.0	286.52
Grapple Skidder - CAT 525C				200 000	2	2	1.54	75.0	115.50
Total (excluding overheads)				-	4	4	4.01	-	402.02

CHAPTER 5: DISCUSSION

This chapter highlights important site-based factors affecting harvesting production time; estimates for total chainsaw felling and grapple skidding times and variation and validity of the prediction model. Production rates and costs of mechanised timber harvesting systems in relation to semi-mechanised systems are discussed to allow for appropriate systems selection.

5.1 Factors affecting felling time

Although the results for felling time in the training set (Table 4.1) showed that the highest adj. R^2 = 56.61%; Cp = 4.34 was achieved in a subset with four factors (dbh, distance, slope and brush density); slope and brush density were not significant in this model subset. This, therefore, implies that a model with two significant factors (dbh and distance, and constant), adj. R^2 = 56.3%; Cp = 3, can be selected as an appropriate predictor. The Cp value indicates the number of variables (including a constant) used in the model for an adj. R^2 of 56.3%.

Further tests confirmed that tree size (dbh) and inter-tree distance were consistently significant predictor factors in the test (Appendix 9) and validation data sets (Appendix 10). It follows, therefore, that chainsaw felling time accounts for 56.3±0.251% of the total model variation (Equation 4.2). However, it is important to note that fuelling and filing elements take about 11.4% of the total felling time. Therefore, the predicted felling time must be multiplied by 1.114 to adequately estimate total delay-free time. These estimates fall within the range of model variances (47-85%) found in timber harvesting productivity literature (Lortz *et al*., 1997; Wang *et al*., 2004; Ghaffarian & Sobhani, 2007; Behjou *et al*., 2009).

Between these two factors, tree size (dbh) was the most important factor affecting felling time. For instance, dbh alone accounted for 53.9% while inter-tree distance contributed only 4.2% of the model variation (Table 4.1). In fact, Ghaffarian and Sobhani (2007) used dbh alone to estimate chainsaw felling time.

Inter-tree distance is still an important factor because it affects not only felling time but also personal safety. Where possible, the operator could minimise it in a stand in order to optimise felling time while maintaining personal safety. However, this is true only up to a certain point, as trees that are too close to each other would lead to hang-ups hence increasing delay times in felling. Inter-tree distance thus needs to be optimised although the factors that appear to have small influence on felling time i.e. terrain factors.

Ground roughness was particularly insignificant in all subsets of the model because the sample only comprised lower categories i.e. 1-3. If the sample had a representative distribution of all categories, the results could have been different. The same argument may be applicable to other terrain variables.

The remaining variation in Equation 4.2, 43.7%, could best be explained by external factors other than dbh and inter-tree distance. Probable external factors would include mechanical condition of the chainsaw and operator motivation factors. There were operational delays due to general cutting chain maintenance works on the machine (i.e. chain fixing and filing).

5.2 Factors affecting skidding time

In the selection of factors affecting timber grapple skidding (Table 4.4), distance, distance squared, volume per cycle, slope and ground condition (except ground roughness) showed significant influence ($P < 0.05$) on skidding time using the training data set. However, these results differed from the results of the test (Appendix 11) and validation data sets (Appendix 12). In the test set, ground condition and slope lost significance to ground roughness while distance, distance squared, volume per cycle, slope, ground condition and ground roughness were all significant in predicting skidding time in the validation data set.

The inconsistences in training, test and validation data set results may be described as a manifestation of collinearity between ground condition and ground roughness in influencing the model. Collinearity exists when the values of independent factors become closely related to each other due to measurement interface among others (Fox, 1991; Joly *et al*., 2012). A post-hoc correlation analysis confirmed relatedness ($R > 0.5$) between ground condition and ground roughness in the model among data sets (Appendix 13). However, these factors were independent of each. The phenomenon diminishes with an increase in number of samples (Joly *et al*., 2012) as confirmed in the validation data set which had relatively a larger sample size.

Based on variance accounts in the model when a subset with one factor is used (Table 4.4), ground roughness (16.39%) is superior to ground condition (6.73%); but when all six factors are in included, ground condition becomes more influential in the model. Field observations showed that the skidder took more time to complete a skidding cycle during rainy days. The fact that wet skidding conditions prevailed only for a short period of time during the study; it may be argued that its effects had more profound effects on skidding time over ground roughness. However, categories 4 and 5 of ground roughness and ground condition could have brought skidding production to a standstill if they were present.

Distance was the most important factor in the model, accounting for 51.01% of the variation, when tested alone. The square of distance was used with the purpose to increase the prediction power of the model. Wang *et al.* (2004) also used a similar distance transformation to increase the goodness of fit of their skidding model.

Slope still affected skidding cycle time within operational ranges of 5-25%. Its effect became more pronounced due to the significance of volume load and ground condition on skidding time. When the skidder is driving downhill loaded, it exerts little force on the engine but it tends to travel faster than when it is driving uphill loaded. In this case, the extraction operation was predominantly uphill. The fact that volume loaded and ground conditions had significant influence on skidding time, it therefore, followed that slope would be inevitably be significant. Similar findings have been confirmed by Lotfalian *et al.* (2007) and Moafi & Lotfalian (2009).

The best model was, therefore, explained by distance, distance squared, volume per cycle, slope and ground condition (adj. R^2 = 62.01%; Cp = 6.49) in training set (Table 4.4) and as expressed in Equation 4.3. Most studies acknowledge the significance of most of these factors (Kluender *et al.* (1997; Egan & Baumgras, 2003; Behjou *et al.*, 2008; Mousavi *et al.*, 2012) with variance estimates ranging from 50-75%. It can be speculated that the unexplained variation (37.99%) was due to factors such as presentation of the butt ends in relation to direction of skidding. Motivation factors due to machine operator might also have influenced the unexplained variation. The source of demotivation was the disagreements on scheduled refuelling hours particularly for a skidder. After 10.3 hours of work a CAT 525 grapple skidder must be re-fuelled to prevent air locking.

Brush density was insignificant the model. This is because compartment visibility was not affected by weather conditions and vegetation undergrowth. Some literature argues that descriptive stand factors (brush density, ground condition and ground roughness) appear to be less significant in timber harvesting models (Wang *et al*., 2004; Ghaffariyan *et al*., 2012; Mousavi, 2012). However, from the practical point of view, the rates at which harvesting operations took place may have inevitably been affected by these factors as shown in Equation 4.3. In addition to production rates, operators tend to be pre-occupied with their safety due to descriptive stand factors (Han and Renzie, 2005). Nevertheless, the inclusion of ground condition in Equation 4.3 demonstrates the flexibility of this model to be applied variably under different moisture related conditions of the skidding ground i.e. very good, good and moderate ground conditions (categories 1, 2 and 3) with maximum precision.

5.3 Validation of the felling and skidding models

Validation is an important component of a prediction model building process. It seeks to evaluate model performance and conformity to prediction (Feng *et al*., 2006). Fig. 4.1 showed a graphical inter-face between observed and predicted felling times. Skidding times were presented in Fig. 4.2. The inter-face ratio between observed and predicted data sets was about 50:50 (i.e. 50% of each of observed and predicted felling and skidding times). The results imply that the graphical estimates due to observed and predicted times were equal for each of the data sets.

With an average delay-free felling time of 1.22 minutes per tree, the side test for Equation 4.2 estimated that 53 trees could be felled per hour (approx. 77.0 m^3 per hour). For a similar full-tree harvesting method and conditions, the recommended chainsaw felling production standard in South Africa is about 40 trees per hour (FS, 2007). This implies that the Viphya chainsaw operators felled more than the recommended production rate applied in South Africa. However, the production standards may be affected by the total number of hours used per week. For instance, Viphya uses a 6 hour (productive) shift for 6 days in a week slightly lesser than South Africa's productive week.

The results (Table 4.3 & Table 4.6) also favourably complied to a statistical validation criteria reported by Amaro (1998) cited in Ajit (2010) where a constant of about 0 and slope of about 1 is an indication of validity between observed and predicted values. However,

Table 4.6 (skidding time results) showed negative constant (α) values about 0. This, (negative constant) according to Halfon (1989), indicates a systematic bias favouring predicted values. Hence, it follows that even if the skidding model was verified correct and validated, it over-estimated the predicted skidding times. A possible reason for this may be attributed to the use of a dummy factor (ground condition) in the model. Garavaglia and Sharma (1998) warn that categorical dummy factors have precision reduction effects on model fit as compared to factors with continuous data. However, a further analysis showed that alpha (α) values were not statistically significant ($P > 0.05$) to reject the hypothesis that observed and predicted skidding times were equal. Therefore, based on graphical and statistical validation evidence, felling and skidding models are deemed appropriate for predictive uses within the conditions similar to their origins.

The recommended hourly production rate of a semi-mechanised system could have been 62.5 m^3 per hour based on FS (2007) against a skidding production rate of approximately 22.0 m^3 per hour based on Equation 4.4. The recommended production rate used in South Africa for chainsaw-grapple skidder combinations was three times greater than that found in the Viphya. Skidding cycle time length might have been the primary source of variation between the former and latter. It can also be speculated that differences in harvesting methods (full-tree or tree length) and presentation of felled trees on the ground might have existed affecting skidding cycle time variations.

5.4 Production rates and costs for semi-mechanised and mechanised systems

Table 4.7 and Table 4.8 showed comparison between semi-mechanised and mechanised harvesting systems, respectively, on production rates and costs. The productivity of the system is evaluated based on the output at the roadside landing. The results imply that the grapple skidder had an increase in productivity when combined with the feller buncher, due to the pre-bunching of trees.

Introduction of a feller buncher enabled the same grapple skidder to increase the production rates from 21.51 m^3 per hour to 75.0 m^3 per hour (under simulated conditions). Similar increased production rates due to harvesting system mechanisation have also be reported by Acuna *et al*. (2008) and LeDoux (2010). The feller buncher regulates the presentation of butts and also pre-bunches felled trees prior to extraction (Han & Renzie, 2005); a process which shortens skidding cycle time whereby increasing the associated production rates.

Therefore, pre-bunching had a positive effect on production cost minimisation for the mechanised system. In comparison to semi-mechanised system, the total hourly cost of mechanised system ($4.01 per m^3 per machine hour) was optimally minimised by a marginal difference of $0.89 per m^3 although a chainsaw operational cost was the least ($0.27 per m^3). These findings were not different from arguments made by Stokes and Hartsough (1993) and, Egan and Baumgras (2003) that the absence of pre-bunching increases the overall costs of timber harvesting.

In summary, the optimum production rate and cost for semi-mechanised system in a full-tree method required a system mix of 3 chainsaws (Appendix 13.1) with 6 grapple skidders with a constraint (bottleneck) of 21.51 m^3 per hour on the skidder (Appendix 13.2). However, the number of chainsaws would increase with further processing of a felled tree into a log at the roadside landing by at least double. The productivity for mechanised system would be maximised using 2 feller bunchers (Appendix 14.1) against 2 skidders with at least 75.0 m^3 per machine hour (Appendix 14.2) extracted to the roadside. It has been shown that machine inventories for semi-mechanised system are generally higher than those for mechanised system; in which case, additional inventory management costs may arise. The constraint in the former would be overcome by having a double shift for a grapple skidder to ensure that excess volume felled by two chainsaws is extracted in time. Alternatively, a second grapple skidder could be bought although harvesting contractors tend to resist this option. However, upgrading to mechanised systems could help to maximise production rates and minimise costs.

CHAPTER 6: CONLUSIONS AND RECOMMENDATIONS

This chapter summarises important findings about the selection of factors affecting chainsaw felling and grapple skidding times, associated prediction models and their validity. Productivity for mechanised systems is also highlighted for application in the Viphya forest plantations. Recommendations for future actions are drawn.

6.1 Conclusions

The study showed that diameter at breast height and inter-tree distance are important factors that best explain felling time prediction models in *Pinus kesiya* stands on the Viphya forest plantations. Occasional elements (fuelling and filing) yielded outlier effects as they are non-randomly distributed. Such elements may be excluded from the model building process but factored in as percentage of the total felling time. It is of paramount importance that the assumptions for regression analyses are not violated in modelling.

In a skidding operation, distance from stump to the roadside landing was the most important factor affecting grapple skidding time. Other factors of significance that contributed to skidding time included volume load, slope and ground conditions. Higher ordinal scale values approaching "very rough" ground roughness would inevitably have significant effect on productivity of a grapple skidder just like ground conditions.

The inclusion of stand descriptive (dummy) factors increased the versatility of the skidding model application. For instance, the skidding model offered more than one ground condition scenario under which its application is feasible. This is particularly important because timber harvesting conditions may not exactly be homogenous in terms of ground wetness, roughness as well as gradient to be adequately represented by a single model. As such, realistic, robust and useful models are those able to predict parameters with acceptable precision taking into account of site variations for wide application.

Both felling and skidding models satisfied the requirements for validation within the conditions of their derivation. The predicted cycle times for skidding were slightly over-estimated. However, there was no statistical evidence to reject that predicted times were indifferent to observed cycle times in both felling and skidding operations.

Mechanised systems appear to be more advantageous than semi-mechanised systems. The former are associated with lower operating costs and inventories with relatively high production rates. The productivity of a grapple skidder is constrained by the absence of pre-bunching operations in semi-mechanised systems. Pre-bunching capability associated with mechanised felling would enable the machines to work on wetter ground with minimum production losses. This would facilitate building of bunches of firmer (as opposed to wetter) ground culminating into reduced site impacts and increased number of cycles per unit time. Further, alignment of felled trees would minimise turns of grapple skidders while assembling the load or beginning the travel loaded phase of the cycle. Therefore, pre-bunching (which is present in mechanised systems) could help to optimise timber harvesting productivity on the Viphya.

6.2 Recommendations

Prediction models are site specific. It is, therefore, recommended that model prediction coefficients developed in this study are used within the conditions similar to their origin for maximum precision.

It is recommended that this study should be replicated in the rainy season to determine the magnitude of effect on parameter estimates since it was largely conducted during the dry season. The effect of different ground roughness and ground condition categories on productivity needs to be researched further. This study would attempt to determine whether collinearity exists or not.

Felling operators should be provided with appropriate cutting chains and guide bars in relation to tree sizes in order to limit chain maintenance activities. Frequent chain maintenance increased felling cycle times to the detriment of productivity. On skidding, the harvest plan should ensure that optimum extraction distances are determined in order to increase productivity.

Mechanised systems should be tested on the Viphya forest plantations in order to confirm simulated results. Self-levelling track feller bunchers would be appropriate for grapple skidder systems particularly in compartments with difficult terrain (high slope grades and wetter ground). In general, it is recommended that a code of harvesting practice is put in place to guide best operational practices in the Viphya forest plantations. The advantages of mechanised systems could be eminent with compliance to best management, operational and environmental practices.

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APPENDICES

Appendix 1. Timber harvesting work cycle break points in a full-tree method

Operation	Element	Start timing	Stop timing
Felling	Walk to tree	Starts walking to tree	Kneels to cut
	Fell	Saw touches the tree	Tree touches down, sound heard
	Delays (operational, personal, mechanical)	Chainsaw stops running	Starts chainsaw
Skidding	Clear	Power Angle Tilt blade lowered to remove slash	Power Angle Tilt blade raised, area free of slash
	Drive empty	Starts moving in-field	Stops in-field
	Change position	Starts reversing in-field	Stops reversing, approaching a log
	Source & grapple	Starts pre-bunching logs	Stops pre-bunching, loads bunch
	Drive loaded & drop	Starts moving out of compartment loaded	Stops at landing and releases grapple
	Turn	Skidder produces smoke, starts moving	Faces in-field
	Align logs	Blade lowered down or grapple opened	Blade raised up or grapple closed
	Delays (operational, personal, mechanical)	Check skidder, engine off, operator off-seat	Skidder starts, operator on-seat

Appendix 2. The number of observations expected for a felling operation

ELEMENT	FREQUENCY	RELATIVE PERCENTAGE
Walk to tree	6	15.0
Clearing	3	7.5
Felling	14	35.0
Filing	5	12.5
Fuelling*	11	27.5
Delays	1	2.5
Total	40	100.0

* Element of primary concern

$$n' = \frac{4x27.5(100-27.5)}{5^2}$$

$n' = 319$

Therefore minimum number of samples based on Equation 2.9:

$n = 267$

Appendix 3. The number of observations expected for a skidding operation

ELEMENT	FREQUENCY	RELATIVE PERCENTAGE
Clear landing or trail	0	0.0
Drive empty	31	23.1
Change position	8	6.0
Bunch and grapple*	48	35.8
Drive loaded and drop	34	25.4
Turn	3	2.2
Align logs	7	5.2
Delays	3	2.2
Total	134	100.0

* Element of primary concern

$$n' = \frac{4x35.8(100-35.8)}{5^2}$$

$n' = 368$

Therefore minimum number of samples based on Equation 2.9)

$n = 194$

Appendix 4. Chainsaw's average elemental times and proportions

Elements	Average time (min)	Percentage
File	0.067	4.7
Fuel	0.095	6.7
Walk to tree	0.210	14.8
Fell	0.852	59.9
Delays	0.198	13.9
Total	1.422	100.0

Appendix 5. Grapple skidder's average elemental times and proportions

Elements	Average time (min)	Percentage
Drive empty	2.990	17.4
Clear	0.460	2.7
Change position	0.590	3.4
Bunch	5.430	31.5
Drive loaded & drop	3.988	23.2
Turn	0.518	3.0
Align	0.930	5.4
Delays	2.305	13.4
Total	17.210	100.0

Appendix 6. Conversion of over-bark to under-bark diameters: step by step

Step 1: 102 disk samples were cut from log ends (butt and thin-end) to represent the full range of stem diameters. Each disk was about 20 mm lengthwise.

Step 2: Diameters over-bark (d_{ob}) of the disks were measured using a manual caliper.

Step 3: Bark on the disks was removed to enable direct diameter under-bark (d_{ub}) measurement with a caliper.

Step 4: Using regression analysis a generic linear function, $d_{ub} = b_0 + b_1 d_{ob}$, was developed to estimate butt, thin-end and breast height diameters.

Step 5: Specific coefficients for D_{ub} at breast height were developed from the averages of butt and thin-end diameter (Step 1).

The quadratic mean diameter of sampled trees was determined as follows:

$$D_q = \sqrt{\frac{\sum dbh^2}{n}}$$

Where:

$D_q =$ Quadratic mean dbh

dbh = Diameter at breast height

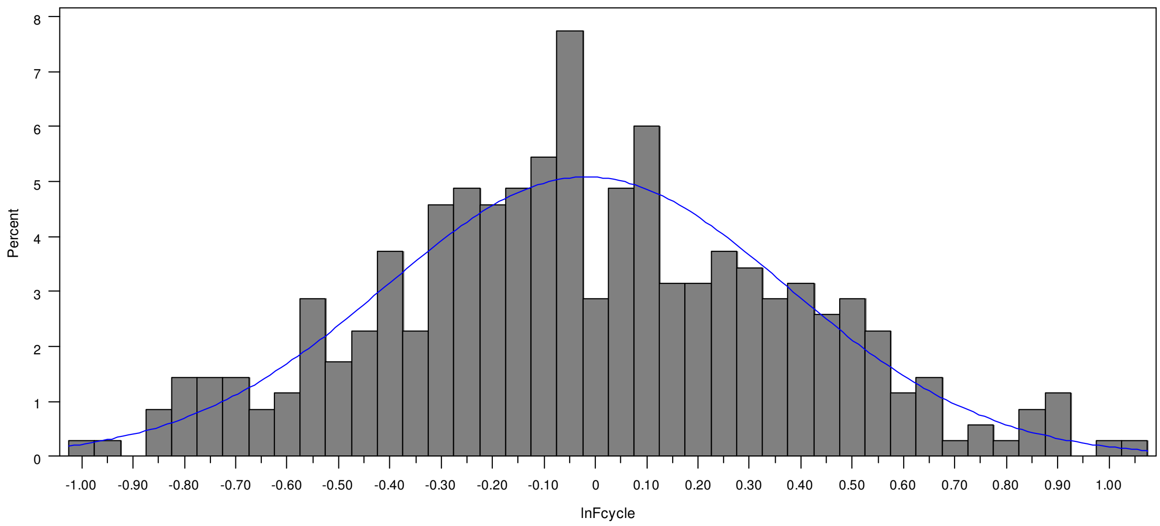
n = Number of observations

The quadratic mean dbh was converted to d_{ub} using steps 4 and 5.

Appendix 7. Normality tests for felling cycle time

```
                         The SAS System        15:33 Friday, April 27, 2012

                   Basic Statistical Measures

         Location                    Variability

     Mean     -0.01771     Std Deviation            0.39204
     Median   -0.04000     Variance                 0.15369
     Mode      0.10000     Range                    2.03000
                           Interquartile Range      0.53000

                   Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  -0.84382    Pr > |t|    0.3994
        Sign           M     -14.5    Pr >= |M|   0.1327
        Signed Rank    S     -1822    Pr >= |S|   0.3306

                      Tests for Normality

   Test                  --Statistic---    -----p Value------

   Shapiro-Wilk          W      0.995568    Pr < W      0.4278
   Kolmogorov-Smirnov    D      0.039727    Pr > D     >0.1500
   Cramer-von Mises      W-Sq   0.049193    Pr > W-Sq  >0.2500
   Anderson-Darling      A-Sq   0.296956    Pr > A-Sq  >0.2500
```

Distribution of skidding times after Box-Cox Transformation



Appendix 8. Normality tests for skidding cycle time

Basic Statistical Measures

Location		Variability	
Mean	3.738519	Std Deviation	0.68522
Median	3.795000	Variance	0.46953
Mode	4.030000	Range	4.04000
		Interquartile Range	0.95000

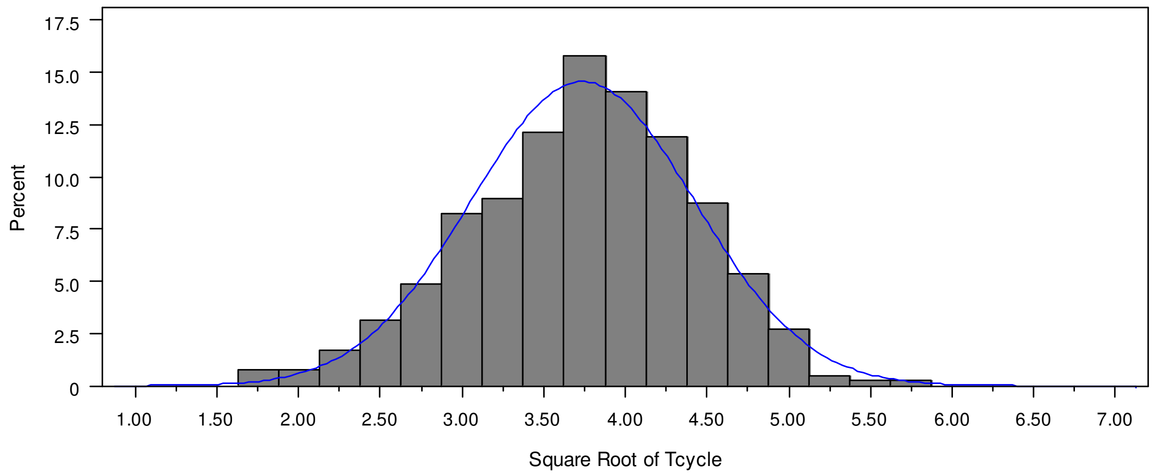
Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	110.7433	Pr > |t|	<.0001
Sign	M	206	Pr >= |M|	<.0001
Signed Rank	S	42539	Pr >= |S|	<.0001

Tests for Normality

Test	--Statistic---		-----p Value------	
Shapiro-Wilk	W	0.9937	Pr < W	0.0845
Kolmogorov-Smirnov	D	0.045021	Pr > D	0.0416
Cramer-von Mises	W-Sq	0.141136	Pr > W-Sq	0.0326
Anderson-Darling	A-Sq	0.809678	Pr > A-Sq	0.0378

Distribution of skidding times after Box-Cox Transformation



Appendix 9. Stepwise selection of the best subset of site-based factors affecting felling time (test set)

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
50.86	15.81	2	.000	-	-	-	-	-
5.46	123.73	2	-	-	-	-	-	.009
1.84	132.07	3	-	-	-	-	.144	-
0.71	135.04	2	-	.190	-	-	-	-
<0.00	137.09	2	-	-	-	.363	-	-
<0.00	138.69	2	-	-	.709	-	-	-

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.09	4.35	3	.000	.000	-	-	-	-
51.94	14.14	3	.000	-	-	-	-	.072
50.55	17.41	3	.000	-	-	.552	-	-
50.41	17.73	3	.000	-	.785	-	-	-
50.17	19.14	4	.000	-	-	-	.748	-
8.10	117.23	4	-	-	-	-	.089	.006
7.57	118.58	3	-	.070	-	-	-	.042
4.91	124.85	3	-	-	-	.526	-	.012

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
58.25	**0.31**	**4**	**.000**	**.000**	**-**	**-**	**-**	**.014**
55.67	6.33	4	.000	.000	.886	-	-	-
55.66	6.35	4	.000	.001	-	.960	-	-
55.49	7.73	5	.000	.000	-	-	.737	-
51.74	15.49	4	.000	-	-	.448	-	.064
51.54	15.96	4	.000	-	.691	-	-	.069
51.10	17.85	5	.000	-	-	-	.879	.091
50.07	19.38	4	.000	-	.876	.584	-	-

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
57.84	2.30	5	.000	.000	-	.920	-	.014
57.84	2.31	5	.000	.000	.984	-	-	.014
57.48	4.14	6	.000	.000	-	-	.918	.019
56.26	6.94	6	.000	.000	.100	-	.192	-
55.23	8.33	5	.000	.001	.885	.954	-	-
55.15	9.47	6	.000	.000	-	.620	.655	-
51.26	17.47	5	.000	-	.895	.512	-	.065
51.02	18.90	6	.000	-	-	.363	.771	.058

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
57.42	4.29	6	.000	.000	.911	.882	-	.015
57.08	6.07	7	.000	.000	-	.797	.893	.022
57.05	6.14	7	.000	.000	.973	-	.918	.096
56.11	8.27	7	.000	.000	.079	.417	.140	-
50.53	20.89	7	.000	-	.907	.451	.774	.196
9.08	114.64	7	-	.005	.689	.423	.240	.028

Best subsets with 6 terms

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.67	8.00	8	.000	.000	.788	.711	.867	.135

Appendix 10. Stepwise selection of the best subset of site-based factors affecting felling time (whole set)

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
52.84	28.00	2	.000	-	-	-	-	-
3.31	419.53	3	-	-	-	-	.001	-
3.20	420.66	2	-	.000	-	-	-	-
1.69	432.54	2	-	-	.009	-	-	-
0.55	441.55	2	-	-	-	-	-	.087
0.35	443.19	2	-	-	-	.138	-	-

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
55.98	4.13	3	.000	.000	-	-	-	-
53.39	24.58	3	.000	-	-	.024	-	-
53.33	25.04	3	.000	-	.031	-	-	-
53.08	27.98	4	.000	-	-	-	.154	-
52.84	28.89	3	.000	-	-	-	-	.311
5.99	398.26	4	-	.001	-	-	.002	-
4.07	413.57	3	-	.000	-	-	-	.042
3.95	414.52	3	-	.003	.055	-	-	-

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.13	3.96	4	.000	.000	-	-	-	.142
56.01	4.89	4	.000	.000	.267	-	-	-
56.00	6.02	5	.000	.000	-	-	.350	-
55.96	5.32	4	.000	.000	-	.371	-	-
53.47	24.87	4	.000	-	-	.018	-	.205
53.45	26.01	5	.000	-	-	.054	.300	-
53.37	25.67	4	.000	-	.027	-	-	.257
53.35	25.85	4	.000	-	.409	.291	-	-

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.18	4.61	5	.000	.000	.245	-	-	.131
56.15	5.81	6	.000	.000	-	-	.342	.138
56.14	4.90	5	.000	.000	-	.304	-	.121
55.94	7.46	6	.000	.000	-	.455	.396	-
55.89	6.85	5	.000	.000	.493	.840	-	-
55.87	7.99	6	.000	.000	.855	-	.638	-
53.63	25.49	6	.000	-	-	.020	.204	.124
53.46	26.82	6	.000	-	.041	-	.262	.066

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.23	**6.20**	**7**	**.000**	**.000**	**-**	**.204**	**.259**	**.072**
56.22	6.28	7	.000	.000	.216	-	.313	.055
56.06	6.49	6	.000	.000	.524	.739	-	.126
55.86	9.12	7	.000	.000	.562	.354	.424	-
53.53	27.27	7	.000	-	.649	.228	.252	.122
6.92	390.58	7	-	.001	.514	.819	.008	.017

Best subsets with 6 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
56.13	8.00	8	.000	.000	.656	.598	.289	.078

Appendix 11. Stepwise selection of the best subset of site-based factors affecting skidding time (test set)

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
45.02	51.33	2	.000	-	-	-	-	-
37.11	75.99	2	-	.000	-	-	-	-
14.96	144.83	3	-	-	-	-	-	.000
11.73	155.06	2	-	-	.000	-	-	-
4.84	176.53	2	-	-	-	.008	-	-
1.56	186.26	3	-	-	-	-	.144	-

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
50.58	34.76	3	.000	.000	-	-	-	-
49.48	38.15	3	.000	-	.001	-	-	-
47.96	43.50	4	.000	-	-	-	-	.014
47.52	44.21	3	.000	-	-	.010	-	-
45.27	51.76	4	.000	-	-	-	.283	-
41.98	61.32	3	-	.000	.001	-	-	-
40.98	64.91	4	-	.000	-	-	-	.008
40.06	67.26	3	-	.000	-	.009	-	-

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
55.58	20.17	4	.000	.000	.000	-	-	-
54.64	23.87	5	.000	-	.000	-	-	.001
53.66	26.87	5	.000	.000	-	-	-	.008
53.26	27.28	4	.000	-	.000	.001	-	-
52.66	29.12	4	.000	.000	-	.013	-	-
51.54	33.30	5	.000	-	.000	-	.031	-
50.35	36.92	5	.000	.000	-	-	.488	-
48.52	42.49	5	-	.000	.000	-	-	.000

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
60.65	6.59	6	.000	.000	.000	-	-	.000
58.88	10.99	5	.000	.000	.000	.001	-	-
56.84	18.09	6	.000	.000	.000	-	.068	-
55.13	23.24	6	.000	-	.000	.132	-	.033
54.26	26.69	7	.000	-	.000	-	.603	.013
53.89	26.97	6	.000	-	.000	.009	.165	-
53.66	27.67	6	.000	.000	-	.318	-	.105
53.00	30.48	7	.000	.000	-	-	.851	.015

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
60.92	**6.79**	**7**	**.000**	**.000**	**.000**	**.182**	**-**	**.019**
60.27	9.73	8	.000	.000	.000	-	.624	.003
59.20	11.94	7	.000	.000	.000	.006	.237	-
55.02	25.28	8	.000	-	.000	.088	.427	.088
53.17	30.75	8	.000	.000	-	.232	.680	.094
48.72	43.96	8	-	.000	.000	.116	.486	.069

Best subsets with 6 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
60.85	9.00	9	.000	.000	.000	.101	.410	.034

Appendix 12. Stepwise selection of the best subset of site-based factors affecting skidding time (whole set)

Best subset with 1 factor

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
49.06	133.26	2	.000	-	-	-	-	-
40.55	229.54	2	-	.000	-	-	-	-
16.24	490.04	3	-	-	-	-	-	.000
7.94	579.21	2	-	-	.000	-	-	-
5.35	606.54	3	-	-	-	-	.000	-
4.33	617.99	2	-	-	-	.000	-	-

Best subsets with 2 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
53.26	93.97	3	.000	.000	-	-	-	-
52.38	103.40	3	.000	-	.000	-	-	-
51.60	111.73	3	.000	-	-	.000	-	-
51.44	114.23	4	.000	-	-	-	-	.000
50.75	121.53	4	.000	-	-	-	.000	-
44.25	190.90	4	-	.000	-	-	-	.000
43.88	194.35	3	-	.000	-	.000	-	-
43.83	194.90	3	-	.000	.000	-	-	-

Best subsets with 3 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
57.37	50.92	4	.000	.000	.000	-	-	-
56.31	62.20	4	.000	-	.000	.000	-	-
56.00	66.39	5	.000	-	.000	-	-	.000
55.49	71.81	5	.000	-	.000	-	.000	-
55.28	74.06	5	.000	.000	-	-	-	.000
55.07	75.47	4	.000	.000	-	.000	-	-
54.29	84.57	5	.000	.000	-	-	.004	-
52.03	108.62	5	.000	-	-	.014	-	.060

Best subsets with 4 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
60.57	18.77	6	.000	.000	.000	-	-	.000
60.42	19.35	5	.000	.000	.000	.000	-	-
59.62	28.77	6	.000	.000	.000	-	.000	-
57.61	50.12	6	.000	-	.000	.000	.001	-
57.04	56.17	6	.000	-	.000	.001	-	.012
56.61	61.62	7	.000	-	.000	-	.022	.002
55.58	71.70	6	.000	.000	-	.053	-	.036
55.27	75.05	6	.000	.000	-	.002	.153	-

Best subsets with 5 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
61.37	**11.21**	**7**	**.000**	**.000**	**.000**	**.000**	**.003**	**-**
61.22	12.82	7	.000	.000	.000	.005	-	.006
60.88	17.34	8	.000	.000	.000	-	.072	.001
57.85	49.45	8	.000	-	.000	.000	.008	.122
55.59	73.33	8	.000	.000	-	.040	.361	.086
50.89	122.89	8	-	.000	.000	.001	.011	.045

Best subsets with 6 factors

Adjusted	Cp	Df	(1)	(2)	(3)	(4)	(5)	(6)
61.77	9.00	9	.000	.000	.000	.001	.021	.046

Appendix 13. Correlation matrices for predicted skidding cycle time, ground condition and ground roughness

Training set (N = 288)

Sqrt (cycle time)	1.0		
Ground condition	0.2658	1.0	
Ground roughness	0.4108	0.5586	1.0
	Sqrt (cycle time)	Ground condition	Ground roughness

Test set (N = 124)

Sqrt (cycle time)	1.0		
Ground condition	0.1580	1.0	
Ground roughness	0.4027	0.4861	1.0
	Sqrt (cycle time)	Ground condition	Ground roughness

Whole set (N = 412)

Sqrt (cycle time)	1.0		
Ground condition	0.2307	1.0	
Ground roughness	0.4079	0.5358	1.0
	Sqrt (cycle time)	Ground condition	Ground roughness

Appendix 14.1. Costing model for semi-mechanised systems: chainsaw

MACHINE DESCRIPTION : Husqvarna 372XP
OPERATION : Felling of full-trees (without debranching and topping)

Note: all figures quoted are estimates, site specific & assume fully trained operators

1.1 CAPITAL EMPLOYED

Machine Price,Exc.VAT		810	US$
Less Cost of Chain/Bar/Sprocket		137	US$
Plus additional equipment	combican	0	US$
	felling lever	0	US$
	other	0	US$
	other	0	US$
	other	0	US$
Sub total additional equipment		0	US$
Total Capital Employed		673	US$
Annual Hp's		743	US$

1.2 HP Calculation

Residual Value @	10.00%	67	US$
Interest per annum		0.00%	
Payment period		12	months
Monthly payment		62	US$

2.1 VEHICLE OPERATING COSTS

Fuel Consumption			1.8	L/Hr
Fuel Cost			1.96	US$/L
Oil/Lube (% Fuel Consumption)			50%	
Oil Cost			7.20	US$/L
Tyres/Tracks/Rigging				
	Qty	Cost	Life	
Bar	1	91	150	
Chain	1	39	38	
Other	0	0	0	
Nose Sprocket	0	34	75	
Rim Sprocket	1	7	75	
Fuel,Cost			3.53	US$/mhr
Oil, Cost			6.48	US$/mhr
Chain/ bar/ files/ Chainsaw pants/ etc.			1.73	US$/mhr
Annual Fuel Costs			4 160	US$
Annual Lube Cost			7 641	US$
Annual Chain/ bar/ files/ Chainsaw pants/ etc.			2 036	US$

3.1 LABOUR COSTS

Operator Wage	0.79	US$/hour
No.Operators/Shift	1.0	#
Labour Wage	0.20	US$/hour
No.Labourers/Shift	1.0	#
Contributions	20.0%	
Operating Days/Week	6.0	days
Operating Hours/Week	48.0	days
Basic Hours/week/operator	48.0	Hrs
Total Overtime per week	0.0	Hrs
Time and a Half per week	0.0	Hrs
Double Time per Week	0.0	Hrs
Shift or Other Allowance	0.00	US$/day
Annual Normal Time	2 289	US$
Annual Time and a Half	0	US$
Annual Double Time	0	US$
Annual Bonus	191	US$
Annual Shift or Other Allowance	0	US$
Annual Contributions	496	US$
Total Annual Crew Cost	2 976	US$
Total Crew Cost per Machine Hr	2.52	US$/mhr

1.3 OPERATING HOURS

Total Days	365	
Weekend Days	52	
Statutory Leave Days	11	
Sick Leave Days	3	
Productive Days Lost to Weather/Mill Stops	10	
Total Annual Production Days	289	*Days*
Shift length	8	*Hours*
Number of Shifts per day	1	*#*
Machine Availability	85.0%	
Machine Utilisation	60.0%	
Machine hours per Day	4.1	*Hours*
Machine hours per Annum	1 179	*Hours*
Machine Life Hours	1 800	*Hours*
Machine Life Years	1.53	*Years*

1.4 OVERHEADS

Annual Licence Fees	16	*US$*

1.5 GROSS PROFIT MARGIN (OPTIONAL)	0.00%	0	*US$*

2.2 VEHICLE MAINTENANCE COSTS

Maint,% Cap.Cost/machine life (mhr)	45%	
Maintenance Cost	0.20	*US$/mhr*
Annual Maintenance Cost	239	*US$*

2.3 RELOCATION COSTS (OPTIONAL)

Number of moves per annum	0	*#*
Cost per Move	0	*US$*
Annual Relocation Cost	0	*US$*
Relocation Cost per Machine Hour	0.00	*US$/mhr*

5.1 MACHINE REQUIREMENTS

Annual Volume	200 000	*m3*
Hourly Volume Required	169.62	*m3/mhr*
Number Of Machines Required	2.39	*#*
Fleet Reserve	10%	
Exact Number of Machines Required	2.62	*#*
Rounded number of vehicles Required	3	*#*

4.1 WORK STUDY ANALYSIS

Average Tree Volume	1.450	*m3*
Filing	0.067	*min*
Fuelling	0.095	*min*
Walk to Tree	0.210	*min*
Felling	0.852	*min*
Debranch/top	0.000	*min*
other	0.000	*min*
other	0.000	*min*
other	0.000	*min*
cycle time	1.224	*min*
cycle time	0.020	*hrs*
Machine Output per Hour	71.08	*m3/hr*
Machine Output per Day	290	*m3/day*
Trees per day	200.00	*trees/day*
Machine Output per Annum	83 810	*m3/year*

6.1 SUMMARY

	PER MACHINE			FLEET	%
	US$/hr	*US$/month*	*US$/year*	*US$/year*	*of Total*
PROFIT	**0.00**	**0**	**0**	**0**	**0.00%**
FIXED COSTS	**3.17**	**311**	**3 734**	**11 203**	**21.0%**
Hp's	0.63	62	743	2 228	4.2%
Crew	2.52	248	2 976	8 927	16.7%
Licence	0.01	1	16	49	0.1%
Permit & Toll fees	0.0		0	0	0.0%
VARIABLE COSTS	**11.94**	**1 173**	**14 075**	**42 225**	**79.0%**
Fuel	3.53	347	4 160	12 480	23.4%
Lubrication	6.48	637	7 641	22 922	42.9%
Chain & bars	1.73	170	2 036	6 107	11.4%
Maintenance	0.20	20	239	716	1.3%
Relocation	0.00	0	0	0	0.0%
TOTAL COST / REVENUE	**15.10**	**1 484**	**17 809**	**53 428**	**100.0%**

6.2 FLEET SUMMARY

US$ per m3	**0.27**
Number of Machines	**3**
Number of Staff	**6**
Machine Hours	**3 537**
Capital Employed	**2 019**
Residual Value	**202**
Total Revenue	**53 428**

Appendix 14.2. Costing model for semi-mechanised systems: grapple skidder

MACHINE DESCRIPTION : Grapple Skidder - CAT 525C
OPERATION : Extraction of full-trees to roadside

Note: all figures quoted are estimates, site specific & assume fully trained operators

1.1 CAPITAL EMPLOYED

Machine Price,Exc.VAT		277 484	US$
Less Cost of Tyres/Tracks/Rigging		17 500	US$
Plus additional equipment	radio	0	US$
	other	0	US$
	other	0	US$
	other	0	US$
	other	0	US$
Sub total additional equipment		0	US$
Total Capital Employed		259 984	US$
Annual HP payment		62 871	US$

1.2 HP Calculation

Residual Value @	10.00%	25 998	US$
Interest per annum		0.00%	
Payment period		48	months
Monthly payment		5 239	US$

2.1 VEHICLE OPERATING COSTS

Fuel Consumption			19.4	L/Hr
Fuel Cost			1.90	US$/L
Oil/Lube (% Fuel Consumption)			2%	
Oil Cost			7.20	US$/L
Tyres/Tracks/Rigging				
	Qty	Cost	Life	
Tyres (front)	2	4 375	6 000	
Tyres (rear)	2	4 375	6 000	
Other	0	0	0	
Other	0	0	0	
Other	0	0	0	
Fuel,Cost			36.86	US$/mhr
Oil, Cost			2.10	US$/mhr
Tyres			2.92	US$/mhr
Annual Fuel Costs			61 359	US$
Annual Lube Cost			3 488	US$
Annual Tyres			4 855	US$

3.1 LABOUR COSTS

Driver Wage	0.69	US$/hour
No.Drivers/Shift	1.0	#
Labour Wage	0.20	US$/hour
No.Labourers/Shift	1.0	#
Contributions	20.0%	
Operating Days/Week	6.0	days
Operating Hours/Week	48.0	Hrs
Basic Hours/week	48.0	Hrs
Total Overtime per week	0.0	Hrs
Time and a Half per week	0.0	Hrs
Double Time per Week	0.0	Hrs
Shift or Other Allowance	0.00	US$/day
Annual Normal Time	2 058	US$
Annual Time and a Half	0	US$
Annual Double Time	0	US$
Annual Bonus	171	US$
Annual Shift or Other Allowance	0	US$
Total Annual Crew Cost	2 229	US$
Total Crew Cost per Machine Hr	1	US$/mhr

1.3 OPERATING HOURS

Total Days	365	
Weekend Days	52	
Statutory Leave Days	11	
Sick Leave Days	3	
Productive Days Lost to Weather/Mill Stops	10	
Total Annual Production Days	289	*Days*
Shift length	8	*Hours*
Number of Shifts per day	1	*#*
Machine Availability	90.0%	
Machine Utilisation	80.0%	
Machine hours per Day	5.8	*mhr*
Machine hours per Annum	1 665	*mhr*
Machine Life Hours	20 000	*mhr*
Machine Life Years	12.01	*Years*

1.4 OVERHEADS

Annual Licence Fees	5 550	*US$*

1.5 Gross Profit Margin	0.00%	0	*US$*

2.2 VEHICLE MAINTENANCE COSTS

Maint,% Cap.Cost/machine life (mhr's)	60%	
Maintenance Cost	8.32	*US$/mhr*
Annual Maintenance Cost	13 857	*US$*

2.3 RELOCATION COSTS

Number of moves per annum	4	*#*
Cost per Move	50	*US$*
Annual Relocation Cost	200	*US$*
Relocation Cost per Machine Hour	0.12	*US$/mhr*

5.1 Machine Requirements

Annual Volume	200 000	*m3*
Hourly Volume Required	120.15	*m3/mhr*
Number Of Machines Required	5.58	*#*
Fleet Reserve	0%	
Exact Number of Machines Required	5.58	*#*
Rounded number of vehicles Required	6	*#*

4.1 WORK STUDY ANALYSIS

Lead Distance	0.134	*km*
Volume per Load	5.2	*m3*
Drive empty	2.7	*km/hr*
other	0.00	*min*
Change position	0.59	*min*
Bunch	5.43	*min*
Drive loaded and drop	2.0	*km/hr*
Turn	0.52	*min*
Align	0.93	*min*
Drive empty time	2.99	*min*
other	0.00	*min*
Change position time	0.59	*min*
Bunching time	5.43	*min*
Drive loaded time	3.99	*min*
Turning time	0.52	*min*
Align time	0.93	*min*
Cycle time	14.44	*min*
Cycle time	0.241	*hrs*
Machine Output per Hour	21.51	*m3/mhr*
Machine Output per Day	123.92	*m3/day*
Machine Output per Annum	35 812	*m3/year*

6.1 SUMMARY

	PER MACHINE			FLEET	%
	US$/hr	*US$/month*	*US$/year*	*US$/year*	*of Total*
PROFIT	**0.00**	**0**	**0**	**0**	**0.00%**
FIXED COSTS	**42.44**	**5 888**	**70 650**	**423 901**	**45.8%**
Hp's	37.77	5 239	62 871	377 228	40.7%
Crew	1.34	186	2 229	13 375	1.4%
Licence	3.33	462	5 550	33 298	3.6%
VARIABLE COSTS	**50.32**	**6 980**	**83 759**	**502 553**	**54.2%**
Fuel	36.86	5 113	61 359	368 152	39.7%
Lubrication	2.10	291	3 488	20 927	2.3%
Tyres	2.92	405	4 855	29 131	3.1%
Maintenance	8.32	1 155	13 857	83 144	9.0%
Relocation	0.12	17	200	1 200	0.1%
TOTAL COST / REVENUE	**92.76**	**12 867**	**154 409**	**926 455**	**100.0%**

6.2 FLEET SUMMARY

US$ per m3	**4.63**
US$ per hr	**100**
Number of Machines	**6**
Number of staff	**12**
Machine Hours	**9 988**
Capital Employed	**1 559 904**
Residual Value	**155 990**
Total Revenue	**926 455**

Appendix 15. 1. Simulated costing model for mechanised systems: feller buncher

Quality - Environment - Safety
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MACHINE DESCRIPTION : John Deere 759JH (Waratah FL85 Chainsaw Felling Head)
OPERATION : Felling and bunching full-trees

Note: all figures quoted are estimates, site specific & assume fully trained operators

1.1 CAPITAL EMPLOYED

Machine Price, Exc.VAT		557 647	*US$s*
Less Cost of Tyres/Tracks/Rigging		35 937	*US$s*
Plus additional equipment	radio	0	*US$s*
	other	0	*US$s*
	other	0	*US$s*
	other	0	*US$s*
	other	0	*US$s*
Sub total additional equipment		0	*US$s*
Total Capital Employed		521 710	*US$s*
Annual HP payment		117 385	*US$s*

1.2 HP Calculation

Residual Value @	10.00%	52 171	*US$s*
Interest per annum		0.00%	
Payment period		48	*months*
Monthly payment		9 782	*US$s*

2.1 VEHICLE OPERATING COSTS

Fuel Consumption			23	*L/Hr*
Fuel Cost			1.90	*US$/L*
Oil,% Fuel Consumption			3%	
Oil Cost			7.20	*US$/L*
Tyres/Tracks/Rigging				
	Qty	Cost	Life	
Bar	1	494	800	
Chain	1	148	100	
Tracks	1	35 295	14 000	
other	0	0	0	
other	0	0	0	
Fuel, Cost			43.70	*US$/mhr*
Oil, Cost			4.97	*US$/mhr*
Tyres/Tracks/Rigging Cost			4.62	*US$/mhr*
Annual Fuel Costs			70 822	*US$s*
Annual Lube Cost			8 051	*US$s*
Annual Tyre/Track/Rigging Cost			7 485	*US$s*

3.1 LABOUR COSTS

Driver Wage	0.69	*US$/hour*
No. Drivers/Shift	1.0	*#*
Labour Wage	0.00	*US$/hour*
No. Labourers/Shift	0.0	*#*
Contributions	20.0%	
Operating Days/Week	6.0	*days*
Operating Hours/Week	48.0	*days*
Basic Hours/week	48.0	*Hrs*
Total Overtime per week	0.0	*Hrs*
Time and a Half per week	0.0	*Hrs*
Double Time per Week	0.0	*Hrs*
Shift or Other Allowance	0.00	*US$/day*
Annual Normal Time	1 914	*US$s*
Annual Time and a Half	0	*US$s*
Annual Double Time	0	*US$s*
Annual Bonus	160	*US$s*
Annual Shift or Other Allowance	0	*US$s*
Total Annual Crew Cost	2 074	*US$s*
Total Crew Cost per Machine Hr	1	*US$/mhr*

1.3 OPERATING HOURS

Total Days	365	
Weekend Days	52	
Statutory Leave Days	11	
Sick Leave Days	3	
Productive Days Lost to Weather/Mill Stops	10	
Total Annual Production Days	289	*Days*
Shift length	8	*Hours*
Number of Shifts per day	1	*#*
Machine Availability	90.0%	
Machine Utilisation	77.9%	
Machine hours per Day	5.6	*Hours*
Machine hours per Annum	1 621	*Hours*
Machine Life Hours	20 000	*Hours*
Machine Life Years	12.34	*Years*

1.4 OVERHEADS

Annual Licence Fees & insurance	11 153	*US$s*

1.5 Gross Profit Margin	0.00%	0	*US$s*

2.2 VEHICLE MAINTENANCE COSTS

Maint,% Cap.Cost/machine life (mhr)	65%	
Maintenance Cost	18.12	*US$/mhr*
Annual Maintenance Cost	29 372	*US$s*

2.3 RELOCATION COSTS

Number of moves per annum	4	*#*
Cost per Move	100	*US$s*
Annual Relocation Cost	400	*US$s*
Relocation Cost per Machine Hour	0.25	*US$/mhr*

5.1 Machine Requirements

Annual Volume	200 000	*m3*
Hourly Volume Required	123.41	*m3/hr*
Number Of Machines Required	1.06	*#*
Fleet Reserve	0%	
Exact Number of Machines Required	1.06	*#*
Rounded number of vehicles Required	2	*#*

4.1 WORK STUDY ANALYSIS

Average Tree Volume	1.45	*m3*
Move to position	0.18	*min*
Fell	0.31	*min*
Swing tree to bunch	0.15	*min*
Swing to next tree	0.11	*min*
other	0.00	*min*
other	0.00	*min*
other	0.00	*min*
other	0.00	*min*
other	0.00	*min*
cycle time	0.75	*min*
cycle time	0.013	*hrs*
Machine Output per Machine Hr	116.0	*m3/mhr*
Machine Output per Day	651	*m3/day*
Machine Output per Annum	187 995	*m3/year*

6.1 SUMMARY

	PER MACHINE			FLEET	%
	US$/hr	*US$/month*	*US$/year*	*US$/year*	*of Total*
PROFIT	**0.00**	**0**	**0**	**0**	**0.00%**
FIXED COSTS	**80.59**	**10 884**	**130 612**	**261 223**	**52.9%**
Hp	72.43	9 782	117 385	234 770	47.6%
Crew	1.28	173	2 074	4 148	0.8%
Licence	6.88	929	11 153	22 306	4.5%
Permit & Toll fees	0.0		0	0	0.0%
VARIABLE COSTS	**71.66**	**9 678**	**116 131**	**232 261**	**47.1%**
Fuel	43.70	5 902	70 822	141 645	28.7%
Lubrication	4.97	671	8 051	16 103	3.3%
Tyres	4.62	624	7 485	14 970	3.0%
Maintenance	18.12	2 448	29 372	58 744	11.9%
Relocation	0.25	33	400	800	0.2%
TOTAL COST / REVENUE	**152.25**	**20 562**	**246 742**	**493 484**	**100.0%**

6.2 FLEET SUMMARY

US$ per m3	**2.47**
Number of Machines	**2**
Number of Operators	**2**
Machine Hours	**3 241**
Capital Employed	**1 043 420**
Residual Value	**104 342**
Total Revenue	**493 484**

Appendix 15. 2. Simulated costing model for mechanised systems: grapple skidder

MACHINE DESCRIPTION : Grapple Skidder - CAT 525C
OPERATION : Extraction of full-trees to roadside

Note: all figures quoted are estimates, site specific & assume fully trained operators

1.1 CAPITAL EMPLOYED

Machine Price, Exc.VAT		277 484	US$
Less Cost of Tyres/Tracks/Rigging		17 500	US$
Plus additional equipment	radio	0	US$
	other	0	US$
	other	0	US$
	other	0	US$
	other	0	US$
Sub total additional equipment		0	US$
Total Capital Employed		259 984	US$
Annual HP payment		62 871	US$

1.2 HP Calculation

Residual Value @	10.00%	25 998	US$
Interest per annum		0.00%	
Payment period		48	months
Monthly payment		5 239	US$

2.1 VEHICLE OPERATING COSTS

Fuel Consumption			19.4	L/Hr
Fuel Cost			1.90	US$/L
Oil/Lube (% Fuel Consumption)			2%	
Oil Cost			7.20	US$/L
Tyres/Tracks/Rigging				
	Qty	Cost	Life	
Tyres (front)	2	4 375	6 000	
Tyres (rear)	2	4 375	6 000	
Other	0	0	0	
Other	0	0	0	
Other	0	0	0	
Fuel,Cost			36.86	US$/mhr
Oil, Cost			2.10	US$/mhr
Tyres			2.92	US$/mhr
Annual Fuel Costs			61 359	US$
Annual Lube Cost			3 488	US$
Annual Tyres			4 855	US$

3.1 LABOUR COSTS

Driver Wage	0.69	US$/hour
No. Drivers/Shift	1.0	#
Labour Wage	0.20	US$/hour
No. Labourers/Shift	0.0	#
Contributions	20.0%	
Operating Days/Week	6.0	days
Operating Hours/Week	48.0	Hrs
Basic Hours/week	48.0	Hrs
Total Overtime per week	0.0	Hrs
Time and a Half per week	0.0	Hrs
Double Time per Week	0.0	Hrs
Shift or Other Allowance	0.00	US$/day
Annual Normal Time	1 595	US$
Annual Time and a Half	0	US$
Annual Double Time	0	US$
Annual Bonus	133	US$
Annual Shift or Other Allowance	0	US$
Total Annual Crew Cost	1 728	US$
Total Crew Cost per Machine Hr	1	US$/mhr

1.3 OPERATING HOURS

Total Days	365	
Weekend Days	52	
Statutory Leave Days	11	
Sick Leave Days	3	
Productive Days Lost to Weather/Mill Stops	10	
Total Annual Production Days	289	*Days*
Shift length	8	*Hours*
Number of Shifts per day	1	*#*
Machine Availability	90.0%	
Machine Utilisation	80.0%	
Machine hours per Day	5.8	*mhr*
Machine hours per Annum	1 665	*mhr*
Machine Life Hours	20 000	*mhr*
Machine Life Years	12.01	*Years*

1.4 OVERHEADS

Annual Licence Fees	5 550	*US$*

1.5 Gross Profit Margin	0.00%	0	*US$*

2.2 VEHICLE MAINTENANCE COSTS

Maint,% Cap.Cost/machine life (mhr)	60%	
Maintenance Cost	8.32	*US$/mhr*
Annual Maintenance Cost	13 857	*US$*

2.3 RELOCATION COSTS

Number of moves per annum	4	*#*
Cost per Move	50	*US$*
Annual Relocation Cost	200	*US$*
Relocation Cost per Machine Hour	0.12	*US$/mhr*

5.1 Machine Requirements

Annual Volume	200 000	*m3*
Hourly Volume Required	120.15	*m3/mhr*
Number Of Machines Required	1.60	*#*
Fleet Reserve	0%	
Exact Number of Machines Required	1.60	*#*
Rounded number of vehicles Required	2	*#*

4.1 WORK STUDY ANALYSIS

Lead Distance	0.134	*km*
Volume per Load	5.2	*m3*
Drive empty	0.0	*km/hr*
other	0.00	*min*
Change position	0.00	*min*
Bunch	0.00	*min*
Drive loaded and drop	0.00	*km/hr*
Turn	0.00	*min*
Align	0.00	*min*
Drive empty time	0.00	*min*
other	0.00	*min*
Change position time	0.00	*min*
Bunching time	0.00	*min*
Drive loaded time	0.00	*min*
Turning time	0.00	*min*
Align time	0.00	*min*
Cycle time	4.16	*min*
Cycle time	0.069	*hrs*
Machine Output per Hour	75.06	*m3/mhr*
Machine Output per Day	432.33	*m3/day*
Machine Output per Annum	124 945	*m3/year*

6.1 SUMMARY

	PER MACHINE			FLEET	%
	US$/hr	*US$/month*	*US$/year*	*US$/year*	*of Total*
PROFIT	**0.00**	**0**	**0**	**0**	**0.00%**
FIXED COSTS	**42.14**	**5 846**	**70 149**	**140 299**	**45.6%**
Hp's	37.77	5 239	62 871	125 743	40.8%
Crew	1.04	144	1 728	3 456	1.1%
Licence	3.33	462	5 550	11 099	3.6%
VARIABLE COSTS	**50.32**	**6 980**	**83 759**	**167 518**	**54.4%**
Fuel	36.86	5 113	61 359	122 717	39.9%
Lubrication	2.10	291	3 488	6 976	2.3%
Tyres	2.92	405	4 855	9 710	3.2%
Maintenance	8.32	1 155	13 857	27 715	9.0%
Relocation	0.12	17	200	400	0.1%
TOTAL COST / REVENUE	**92.46**	**12 826**	**153 908**	**307 816**	**100.0%**

6.2 FLEET SUMMARY

US$ per m3	**1.54**
US$ per hr	**115**
Number of Machines	**2**
Number of staff	**2**
Machine Hours	**3 329**
Capital Employed	**519 968**
Residual Value	**51 997**
Total Revenue	**307 816**