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Research Paper

Productivity and costs modeling for tree harvesting operations using chainsaws in plantation forests, Tanzania

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Abstract

With exemption of a few private forests, timber harvesting in most plantation forests in Tanzania is carried out by less skilled and less equipped crews. Newly recruited crews often learn from experienced ones which may not be doing it in the perfect way. Therefore estimation and projecting production and costs becomes a big problem to logging managers. This study was carried out to develop productivity and costs models for chainsaw operators in a learning experiment. The experiments were designed in clear felling operations. Three experiments were set where each crew category was studied using time study and work sampling techniques that involved studying crews before training, after training and after the break at an interval of three months. Descriptive statistics and modelling was performed for each crews' performance. Specific crew's productivity and costs models have been developed reflecting necessary and unnecessary delay times. Assessment of the production costs show that unit costs decreases with increasing productivity in each unit of measurement of the production rate. It is recommended that productivity and costs for two-man crosscut saw operators be studied and modelled since they are also the main cutting tools used in tree cutting in Tanzania.

Keywords: *Productivity, Cost, Timber Harvesting, Modelling, Chainsaw, Tanzania.*

1. Introduction

Designing timber harvesting units is one of the most difficult tasks in forest operational planning [4] [23]. The task requires forest engineers to decide on logging equipments, landing site, logging profile, transportation systems, and road location based on various considerations, including timber volume distribution, economic and environmental outcomes, as well as the physical feasibility of the system. In forestry harvesting productivity and costs may vary depending on some variables like stand and timber characteristics (tree density, volume per ha, species, branch-ness and sizes), terrain conditions, climatic conditions where wood is being harvested [18]. They may also vary depending on the type of equipment and machinery used, the harvesting system used, physical work capacity, nutrition, health and training levels of the workers. Therefore, these variables need to be combined in a feasible way that optimizes operations.

Productivity may be defined as units of production per unit of time being in ratios of output to input [12] [16]. Each operation requires a productivity measure, which reflects its effectiveness and can be made available on timely basis. Productivity is frequently measured in terms of output of goods or services in a given number of 'man-hour' or 'machine-hours' [22]. For instance, higher production per unit of area over a given period of time generally means that production per worker is raised, although productivity per worker and per hectare does not necessarily match in step. Production per hectare may be increased by intensive methods without raising labour productivity, and mechanization or rationalization of work methods may raise labour productivity without necessarily raising total production [11].

Logging productivity is affected by many factors that are interrelated, and one or more may be independent of the other. For example, all the environmental, social, political, labour (worker), economic factors as well as the applied system influence logging productivity. Improving technology (mechanization and planning) of harvesting in many parts of the world is expected to lower the risks associated by these factors. Unlike in developed countries where mechanization in timber harvesting is applied, traditional methods (basic technologies) are still being used in developing countries [1] including Tanzania, which in most cases give low productivity. The equipments used in timber harvesting in Tanzanian forests are partly those introduced three decades ago when intensive harvesting started.

Despite development of timber harvesting technology in the world logging industry in Tanzania has failed to cope with the changing technology due to several reasons including poor economic power and lack of 'commitment' from logging companies. Static technology has over many years resulted into systemic poor productivity. For example, the highest average productivity reported in Tanzania from chainsaw cutting was $3.5m^3$ per man-day [19]. In Swedish forestry industry productivity had increased from $2.3m^3$ to 12.5 m^3 between 1960 and 1990 while mechanized felling productivity did increase by 85% in that period [2].

Although introduction of chainsaws in the early 1960 in Swedish industrial forestry resulted into a great change in productivity, their use has decreased shapely due to introduction of high technology harvesters [2]. A study conducted in Norway indicated that introduction of mechanization in industrial forest has improved productivity especially in clear felling operations but the system has shown higher injury rate to residual stands than it could have been when motor-manual (chainsaws) and cable logging is used [10]. With these few observations the trend shows that there have been high achievements in the logging productivity that cannot be comparable to the current situation in Tanzania.

Timber harvesting in Tanzania is performed by less skilled workers which affect both productivity and safety of crews [24]. Although most investors in forestry industry recognize the importance of engaging professional staff for optimizing operations, they have made use of policy vacuums and availability of cheap labour to engage less and ill-skilled personnel in harvesting operations. This is due to the fact that about 75% of the Tanzanian population lives in rural areas [13] where most of them survive with low income under poor social infrastructures [25]. Since most forests border these populations, workers with little knowledge of forest work can often be engaged at low wage rates. Therefore, workers are given in-service training and thus most learning takes place on site. Therefore it is important to simulate productivity and costs of expected crews in harvesting operations to assist logging managers and other planners in scheduling for optimum logging operations.

2. Material and methods

2.1. Description of the study area

This study was carried out at the Sokoine University of Agriculture Training Forest, (SUATF) Olmotonyi, in Arusha region, Tanzania which is part of the Meru Plantaiton forests. It lies between latitudes 3' 15º – 3' 18º south and longitudes 36' 41º – 36' 42º east. The main tree species grown include *Cupressus lusitanica*, *Pinus patula*, E*ucalyptus sp*., *Grevillea robusta* and *Acacia sp.* SUATF is on the slopes of Mount Meru, at between 1740 to 2320 m above sea level. The seasonal climate includes a consistently dry period between June and October. Rainfall patterns vary considerably, but average annual precipitation is about 1200 mm. The mean annual temperatures range between 18°C in the morning to 23°C in the afternoon [24]. During this study, logging was carried out using common tools used in other forest plantations in Tanzania. Tree cutting was done by using two man crosscut saws. Skidding was done manually, by semi-mechanised methods using farm tractors as well as by using oxen while hauling was performed using farm tractors fitted with trailers.

2.2. Experimental design

2.2.1. Study groups

The crews were divided into two groups. The first consisted of newly recruited operators (start-up crews) which were engaged during the study and the second group consisted of experienced operators (crews with experience in tree cutting). Each group was first studied in situ for up to three months, then trained and studied after which they break and studied again for the same period of time.

Start-up crews

Crews in this category were made up of individuals without prior experience in tree cutting operations. The chainsaw operator was a man aged 29 years old. He had occasionally been involved in different forest related activities including carrying out forest inventory, log skidding and log loading as a casual labourer for over four years.

Experienced crews

Crews in this category comprised individuals who had previously been involved in tree cutting operations using the chainsaw. This category involved a motor-manual chainsaw operator who had worked for over 8 years in the same forest as an operator. Prior to his current assignment he had been involved in different activities including work at the tree nursery, log skidding and loading. The crew (31 years old) revealed that he did not receive any formal training on either logging operations or chainsaw tree cutting operations. He learned the operation of the chainsaw from a retired operator while assisting him in tree cutting for about two months in thinning operations which are considered less intensive.

2.2.2. Training plan

The training programme focused on hands-on skills based on the recommended tree cutting practices such as directional felling, proper limbing and bucking practices, appropriate ergonomic postures during tree cutting, proper use and maintenance of cutting tools and chainsaws. Accident prevention and safety precautions were also emphasized to reduce workplace accidents and risk hazards. The methods for safety and health training ranged from passive, information based techniques (e.g., lectures) to learner-centred performance-based techniques (e.g., hands on demonstrations), hypothesising that greater knowledge acquisition and more transfer of training to work setting will occur (thereby improving behaviours safety performance and reducing negative safety and health outcomes). Training incorporated specific group requirements. Swahili language was used for instructions. After the training sessions, field work and work studies were then performed concurrently. Tree cutting productivity and costs were then determined based on the time studies techniques.

2.3. Data collection

Productivity studies of tree cutting operations were performed on clear felling operations. Snap-back (zero-reset) time study methods were used to collect data on productive and delay times. This method provided immediate insight into the operation being studied as observed. Selected independent variables that might affect tree cutting productivity, costs and workers' learning rates were measured and recorded concurrently during the time studies. The selected variables measured and recorded were; stump diameter and diameter at breast height (over bark), in centimetres, tree height, in meters, number of logs bucked, log lengths, in centimetres, number of trees cut per day, and terrain slope in percentages. Labour, equipment and machine costs (fixed and variable costs) were obtained from both primary and secondary sources. Equipment and machinery costs included: purchase price, depreciation, interest, taxes, oil, fuel, lubricants and insurance costs. Labour costs included direct wages and other indirect costs like incentives and fringe benefits

2.4. Data analysis

Descriptive statistical analysis, regression analysis and economic (costs) analyses were performed. Descriptive statistics and regression models were developed to establish relationships between dependent and independent variables using MINITAB 15 Computer Software. The dependent variables were time for; felling (TFell), limbing (TLimb), measuring (TMeas), bucking (TBuck) and the total cutting (TCut) time (excluding delays) all recorded in minutes. The independent variables were; stump diameter (over-bark), (SDia in cm), stump basal area (over-bark) (SBA in cm^2), diameter at breast height (over-bark) (Dbh in cm), total tree height (THgt in m), number of logs cut from an individual tree (NLogs), total log length (TLogL in m), log volume (over-bark) (LVol in m^3), total log volume (over-bark), (TLvol in m^3), total tree volume (over-bark) (TTvol in m^3), necessary delay (ND) and unnecessary delay (UND) all recorded in minutes.

2.4.1. Delay time analysis

Delay times are times that are not related to effective working time. The delays were categorized as being necessary (or technical) and unnecessary (being personnel and or operational). The analysis of the delay times was based on the total observation of the individual element that contributes to such a delay. For example, instead of measuring the time used for moving separate from brushing, all these were recorded and analyzed under 'preparation' time component. The preparation time which forms part of the necessary delay has been analyzed separate in this study as it constitutes a reasonable portion of the necessary delay time and was easy to be recorded in the field.

2.4.2. Descriptive time study statistics

Descriptive statistics were performed based on crew category (start up and experienced) and the experimental phase which included a study before training, after training and after the break. This section presents and discusses summary statistics for the dependent and independent variables.

2.4.3. Production rate estimates

Productivity and economic results were derived from the time and motion studies of the tree cutting operation. Multiple regression analysis was performed to develop productive time models that can be used to estimate tree cutting time as a function of the selected independent variables. The models developed were then used to estimate production rates of the tree cutting operations. The Smalian's formula (Eq. 1) was used in computing log volumes [7].

$$V = \left(\frac{A_1 + A_2}{2}\right)L \quad (1)$$

Where;
V = log volume of the log in cubic metres (m^3),
A_1 = area of the log small end in square metres (m^2),
A_2 = area of the log large end in square metres (m^2), and
L = log length of the log in metres (m).
Since productivity is frequently measured in terms of output of goods or services in a given number of 'man-hour' or 'machine-hours' [12] [22], the volume produced in a given cutting operation and the time estimated from regression models were therefore used to compute productivity in m^3/hr (Eq. 2).

$$P = \frac{(T_{vol})(F)(60)}{T} \quad (2)$$

Where:
P = productivity in m^3/hr for a given logging operation, T_{vol} = total volume of all logs for a given logging operation, 60= number of minutes in a workplace hour, F = proportion of productive time per workplace hour, (Eq. 3), T = total productive time (minutes) (estimated using the derived regression models),

$$F = \frac{100 - D}{100} \quad (3)$$

Where: F = a fraction measuring the proportion of productive time, D = delay time expressed as percentage of workplace time.

2.4.4. Estimation of production costs

Production costs were determined by analysing both fixed and variable costs of the machines and labour. Labour costs were computed based on the [8] protocol. The scheduled working hours per day for the chainsaw crews were 6 which amount to 180 days per year. Machine costs were estimated based on the rule of thumb approach by [21], Eq. (4).

$$C_d = 2 * A * 10^{-3} + 5 \quad (4)$$

Where;
C_d = machine cost US$ per day (TShs/day), exclusive of operator, A = purchase price of the machine, US$ (transformed into TShs). Production costs were first computed for each crew category on annual basis. The annual costs in Tanzanian Shillings (TShs) were then converted into hourly costs in (TShs/hr) (Eq. 5).

$$Hourly\ costs\ (TShs / hr) = \frac{Annual\ costs\ (TShs / year)}{(Working\ days\ per\ year * Working\ hours\ per\ day)} \quad (5)$$

The unit costs of production were estimated based on the hours that crews were involved in cutting operations in the field as well as on the amount of wood produced (i.e. production rates in m^3) (Eq. 6). The amount of wood produced was further divided into the actual volume of logs produced and on the basis of the whole trees volume which represents the total volume felled.

$$Unit\ production\ cost\ (TShs / m^3) = \frac{Hourly\ cost\ (TShs / hr)}{Production\ rate\ (m^3 / hr)} \quad (6)$$

2.4.5. Multiple regression analysis

In this study, multivariate and univariate (where appropriate) regression were used for modelling. Two different techniques were applied to develop models for the time consumption in some cases. Firstly, a delay-free time consumption model was developed separately for each element of the work phase assuming that there were no delays which is of course impossible under natural conditions and secondly, time consumption models that excludes unnecessary delay times were developed separately for each element of the work phase on assumption that unnecessary delays could be avoided with training and proper supervisions. Therefore, regression equations have been developed for tree felling (notch cut and felling cut), limbing, measuring, bucking and total cutting times.

3. Results and discussion

3.1. Tree volume modelling

In a volume equation, volume is predicted as a function of diameter at breast height (Dbh), or Dbh and height (h) and some other tree characteristics (x_i) such as form quotient, or form point [14]. Therefore, a relationship between the tree diameters at breast height, tree height and the tree volume were developed for each experiment. Regression hypothesis for the relationship of Dbh, h, and x_i to Tree Volume was developed. Eg. (7), Thus;

$$V = f(Dbh, h, x_i) \quad (7)$$

However, the variable x_i was dropped because according to [14], although it 'x_i' attempts to reduce the volume of a cylinder to tree true volume, the efficacy of this variable, however, is limited as the stem profile is irregular. Thus Eq. (8);

$$V = f(Dbh, h) \quad (8)$$

On development of the volume models for each crew category and for each experiment, all variables were found to have a significant contribution to the volume estimation. However, the variable height was not included because it did not show significant improvement (when comparing the R-square values) from when Dbh alone is included. The developed models were as follows;

3.1.1. Tree volume models for experienced operator

Before training

$$TVol = -2.35 + \underset{(0.002206)}{0.13Dbh}, \ R^2 = 0.911, \ n = 339 \quad (9)$$

After Training

$$TVol = -2.37 + \underset{(0.002515)}{0.13Dbh}, \ R^2 = 0.915, \ n = 250 \quad (10)$$

After the break

$$TVol = -2.58 + \underset{(0.00263)}{0.139Dbh}, \ R^2 = 0.92, \ n = 341 \quad (11)$$

3.1.2. Tree volume models for inexperienced operator

Before training

$$TVol = -2.35 + \underset{(0.002638)}{0.13Dbh}, \ R^2 = 0.893, \ n = 341 \quad (12)$$

After Training

$$TVol = -2.35 + \underset{(0.002206)}{0.13Dbh}, \ R^2 = 0.911, \ n = 136 \quad (13)$$

After the break

$$TVol = -2.34 + \underset{(0.001923)}{0.13Dbh}, \ R^2 = 0.916, \ n = 419 \quad (14)$$

Results show that the coefficient of determination of the two regressed variables (Dbh and TVol) for all the experiments was high ranging between 0.892 and 0.94. This indicates high correlation which may imply an existence of a linear trend between the two variables [15]. Therefore it can be concluded that most of the variation in tree volume determination under this study were explained by proportional variations in Dbh. These observations imply that the equation can be used with high degree of confidence to predict tree volume for similar stands if Dbh is measured in the field. What is important is the consistence of measuring the Dbh. Because according to [20] [5] [3] and [26] there have been inconsistence within longitudinal studies regarding the point where Dbh is recorded which calls for early specification on initiating studies.

3.2. Tree cutting production rate equations

The total cutting time consumption and the tree volume estimate models were substituted in the general model of production rate (Eq. 2) to generate production rate models. These models were developed first by considering the delay free models and secondly the necessary delays included. This assumes that unnecessary delays can be significantly reduced or eliminated by improved supervision and training of the operators. Therefore, the production rate models for cutting time and their respective values of 'F' (i.e. a fraction of the productive minutes per tree) are as follows;

3.2.1. Tree cutting productivity models for experienced operator

The production rate equation of the experienced operator when studied before training with only effective time included;

$$P_{\exp CS} = \frac{-88.83 + 4.914Dbh}{-2.86 + 0.143Dbh + 1.06NLogs} \quad (15)$$

With necessary delay time included;

$$P_{\exp CS} = \frac{-88.83 + 4.914Dbh}{-2.32 + 0.178Dbh + 1.2NLogs} \quad (15)$$

The production rate equation of the experienced operator when studied after the training with only effective time included;

$$P_{\exp CS} = \frac{-100.62 + 5.421Dbh}{-2.72 + 0.146Dbh + 0.971NLogs} \quad (16)$$

With necessary delay time included;

$$P_{\exp CS} = \frac{-100.62 + 5.421Dbh}{-1.90 + 0.135Dbh + 1.15NLogs} \quad (17)$$

The production rate equation of the experienced operator when studied after the break with only effective time included;

$$P_{\exp CS} = \frac{-102.168 + 5.5044Dbh}{-2.26 + 0.111Dbh + 0.984NLogs} \quad (18)$$

With necessary delay time included;

$$P_{\exp CS} = \frac{-102.168 + 5.5044Dbh}{-1.90 + 0.135Dbh + 1.15NLogs} \quad (19)$$

3.2.2. Start-up chainsaw operator production rate equations

The production rate equation of the start-up operator when studied before training in-situ with only effective time included;

$$P_{u\exp CS} = \frac{-71.91 + 3.978Dbh}{1.78 + 0.093Dbh + 1.29NLogs} \quad (20)$$

With necessary delay time included;

$$P_{u\exp CS} = \frac{-71.91 + 3.978Dbh}{1.84 + 0.0122Dbh + 2.36NLogs} \quad (21)$$

The production rate equation of un-experienced operator when studies after the training with only effective time included;

$$P_{u\exp CS} = \frac{-95.88 + 5.304Dbh}{-2.4 + 0.0955Dbh + 1.19NLogs} \quad (22)$$

With necessary delay time included;

$$P_{u\exp CS} = \frac{-95.88 + 5.304Dbh}{-3.27 + 0.187Dbh + 1.22NLogs} \quad (23)$$

The production rate equation of un-experienced operator when studied after the break with only effective time included;

$$P_{u\exp CS} = \frac{-91.26 + 5.07Dbh}{-2.62 + 0.135Dbh + 1.09NLogs} \quad (24)$$

With necessary delay time included;

$$P_{u\exp CS} = \frac{-91.26 + 5.07Dbh}{-2.9 + 0.198Dbh + 1.2NLogs} \quad (25)$$

3.3. Tree cutting productivity

Tree harvesting productivity was calculated on the basis of the number and volume (m^3) of trees cut per hour. Production volume analysis was performed separately based on the logs produced as well as based on the whole tree volume. The production rates when the volume of whole trees and volume of produced logs is considered are shown in tables 1 and 2 respectively.

Table 1: Production Rates When Considering the Whole Tree Volume

Crew category	Before training			After training			After break		
	EfT	EfT+ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays
Experienced crew	14.67	10.12	9.2	15.12	12.12	9.62	19.0	13.65	12.11
Start-up crew	13.37	7.69	7.05	20.36	13.25	12.51	14.95	10.22	9.28

Key: EfT = is the effective productive time (which excludes all delays); ND = is the necessary delays while 'All delays' refers to both Necessary and Unnecessary delays.

Table 2: Production Rates when Considering the Volume Logs Produced

Crew category	Before training			After training			After break		
	EfT	EfT+ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays
Experienced crew	6.06	4.21	3.83	6.16	5.05	3.96	7.67	5.39	4.77
Start-up crew	5.63	3.19	2.93	8.02	5.31	5.02	6.18	4.28	3.89

Key: EfT = is the effective productive time (which excludes all delays); ND = is the necessary delays while 'All delays' refers to both Necessary and Unnecessary delays.

The results showed that there is an increase in production rate of the crews after training with a subsequent fall as the crews resumed cutting operations after the break (Table 3). However, the increase is more significant for the start-up crews as compared with the experienced ones. In a more unusual one, experienced crew showed to have improved after the break as compared with the situation after the training. This scenario can probably be explained by several reasons including ‘conditional motivation’ from the breaking. That is to say the break itself probably served as a motivation to the crew, the accumulated knowledge during training and that knowledge depreciation in experienced operators is relatively lower than those fresh operators depending on the time break. Overall, tree cutting productivity may be influenced by the operator’s skills and motivation, silvicultural method, tree species, stand composition, undergrowth trees and seedlings, weather conditions, the age of the chain saw, chainsaw condition (sharp or dull), and lean of tree as well as terrain slopes. However, the influences of all these factors were not undertaken in this study, but are mentioned and documented by [6].

Table 3: Production Rates (Number of Trees Cut/Hr.) Estimates

Crew category	**Before training**			**After training**			**After break**		
	EfT	EfT+ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays
Experienced crew	12	8.4	7.6	12.7	9.1	8.2	14.2	10.2	9.2
Start-up crew	11.6	6.5	5.9	13.6	9.7	9.8	11.9	8.5	7.7

Key: EfT = is the effective productive time (which excludes all delays); ND = is the necessary delays while ‘All delays’ refers to both Necessary and Unnecessary delays.

There were no similar studies of the same setup available in Tanzania to compare these results directly. Nevertheless, according to a study performed in Congo [9] where the study conditions had some similarity to this one (manual felling by means of chainsaw using untrained operators), the average number of trees cut per day was 20 and the average tree volume was 6.0 m^3 while [17] found approximately 12 tree per day.

3.4 Tree cutting production costs

Assuming that all crews worked as described above, and the costs are estimated based on the 2012/13 price levels, the hourly costs would be TShs 1265. The unit volume production costs (Shs/m^3) for these crews are shown in Table 4 while the cost of cutting a singles tree with effective and delay times included is shown in Table 5.

Table 4: Estimated unit costs for the cutting operations by using chainsaw

Crew category	**Before training**			**After training**			**After break**		
	EfT	EfT+ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays
Experienced crew	206.12	295.70	327.88	205.79	285.05	318.79	166.97	233.08	262.57
Start-up crew	225.20	394.27	429.02	164.58	235.68	230.53	209.88	295.01	325.35

Key: EfT = is the effective productive time (which excludes all delays); ND = is the necessary delays while ‘All delays’ refers to both Necessary and Unnecessary delays.

Table 5: Estimated Unit Costs for the Cutting Operations by Using Chainsaw

Crew category	**Before training**			**After training**			**After break**		
	EfT	EfT+ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays	EfT	EfT + ND	EfT + All Delays
Experienced crew	84.88	122.75	136.38	83.43	117.30	130.61	66.23	92.72	104.51
Start-up crew	85.40	163.73	178.76	63.60	93.95	91.25	86.90	123.11	136.09

Key: EfT = is the effective productive time (which excludes all delays); ND = is the necessary delays while ‘All delays’ refers to both Necessary and Unnecessary delays.

Results show that the unit cost of cutting operations was mostly affected by labour costs. For example labour cost accounted for 61%. In comparison, start-up crew had higher unit costs at the beginning of the operation as compared with the experienced crew. However, the start-up crew observed a significant cost decrease after training. For example the start-up crew had about 40% cost fall after training. Generally, except for the experienced crew, the start-up crew observed a significant costs increase as they resumed operations.

Unit costs decreases with increasing productivity in each unit of measurement of the production rate. In this study the production costs were investigated and compared only from an economic and technical point of view. For example, the unit cost of both machine have been considered as a single unit on the understanding that replacement of mechanical components, servicing, repair and maintenance of each individual machine will not have very different life expectancies. The cutting costs reported by this study especially for the start-up crews are somehow in line with findings from elsewhere in Tanzania especially those results before the training. However, it should be borne in mind that variations in figures between experiments and or between studies may be explained by the fact that harvesting productivity and costs in forestry may vary depending on some variables like timber type and sizes, terrain conditions, climate conditions where wood is being harvested [18] but also the type of equipment and machinery used, the harvesting system used and the health and training levels of the workers.

3.5. Production costs modelling

The general model for calculating the unit production costs can be expressed as Eq. (26).

$$C_C = \frac{CC}{P_r} \quad (26)$$

Where: C_C = unit tree cutting cost, TShs/m^3, CC = total cutting cost, in TShs per working hour, P_r = cutting production rate m^3/hr.

By assuming that it is possible to eliminate all of the unnecessary delays and that all the necessary delay variables affect the unit production costs, the costs models have been developed by considering production equations with necessary delays included for all crews. Each experiment is also modelled separately by considering the unit volume of the logs produced. The unit costs models have therefore been developed by substituting equations 15 through 25 (those with necessary delay time only) into eq. (26) of which the models are as follows;

3.5.1. Production unit cost models for experienced chainsaw operator

The unit production cost equation of the experienced operator when studies for the first time in-situ. Eq. (27).

$$C_C = \frac{-2934.8 + 225.17Dbh + 1.2NLogs}{-88.83 + 4.914Dbh} \quad (27)$$

The unit production cost equation of the experienced operator when studied for after the training;

$$C_C = \frac{-2403.5 + 170.77Dbh + 1454.75NLogs}{-100.62 + 5.421Dbh} \quad (28)$$

The unit production cost equation of the experienced operator when studied for after the break;

$$C_C = \frac{-2403.5 + 170.77Dbh + 1454.75NLogs}{-102.168 + 5.5044Dbh} \quad (29)$$

3.5.2. Production unit cost equations for the startup chainsaw crew

The unit production cost equation of the start-up operator when studied for the first time in-situ;

$$C_C = \frac{2327.6 + 15.43Dbh + 2985.4NLogs}{-71.91 + 3.978Dbh} \quad (30)$$

The unit production cost equation of the start-up operator when studies for after the training;

$$C_C = \frac{-4136.55 + 236.55Dbh + 1543.3NLogs}{-95.88 + 5.304Dbh} \quad (31)$$

The unit production cost equation of un-experienced operator when studied for after the break;

$$C_C = \frac{-3668.5 + 250.47Dbh + 1518NLogs}{-91.26 + 5.07Dbh} \quad (32)$$

4. Conclusion and recommendations

This study has developed productivity and production costs models that are necessary for logging manager to plan for timber harvesting operations with different crew categories. The finding showed that in a more unusual way the experienced crews showed some improvement even after the break. This could be attributed by the fact that they were being observed by the researcher which alone acted as supervision. The production rates observed in this study were 58% and 22% higher as compared to the findings observed earlier by other researchers when studied timber harvesting operations using chainsaw in many parts of Tanzania. Results for the production costs showed that the hourly costs were TShs 1 265. The unit production costs were mostly affected by the labour costs which accounted for 61%. The crews observed a significant cost decrease at an average of 45% after the training. This observations show the need for on job training to all logging crews despite their experience and prior skills and knowledge.

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