Journal of Tropical Forest Science 24(3): 368–378 (2012)

OPERATIONAL EFFICIENCY OF RIMBAKA TIMBER HARVESTER IN HILLY TROPICAL FOREST

K Norizah, I Mohd Hasmadi*, J Kamaruzaman & MS Alias

Forest Surveying and Engineering Laboratory, Faculty of Forestry, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia

Received July 2011

NORIZAH K, MOHD HASMADI I, KAMARUZAMAN J & ALIAS MS. 2012. Operational efficiency of RIMBAKA timber harvester in hilly tropical forest. This paper presents a description of working pattern and results of productivity and cost studies of the RIMBAKA R2020-A Timber Harvester (RIMBAKA harvester). The RIMBAKA harvester was introduced in 2001 to work in tropical forest condition for extracting felled timber to roadside logyard. Field trials were established in the compartment 484-A Ulu Jelai Forest Reserve, Pahang, Peninsular Malaysia. Analyses of time-study data were carried out using analysis of variance and regression techniques to examine significant levels of observed variables and produce prediction equations for each elemental time, hourly productivity and unit cost. Results showed that the RIMBAKA harvester operation extracted 3.55 m^3 of log per cycle and had a machine utilisation rate of 74%, where the productivity was 46.39 m^3 for every productive machine hour. Cost of using RIMBAKA harvester was RM12.70 m^{-3}. Thus, the RIMBAKA harvester system had some advantages over ground-based skidders. A higher production rate of RIMBAKA harvester will be able to reduce cost of operation.

Keywords: Cost study, skidders, time consumption, work productivity, machine production rate

NORIZAH K, MOHD HASMADI I, KAMARUZAMAN J & ALIAS MS. 2012. Kecekapan operasi penuai balak RIMBAKA di hutan bukit tropika. Kertas ini membentangkan huraian pola kerja dan hasil produktiviti serta kajian kos terhadap jentera penuai balak RIMBAKA R2020-A (RIMBAKA). RIMBAKA telah diperkenalkan pada tahun 2001 untuk mengeluarkan kayu balak yang ditebang ke tepi jalan atau matau sementara di hutan tropika. Ujian lapangan telah dilaksanakan di kompartmen 484-A, Hutan Simpan Ulu Jelai, Pahang, Semenanjung Malaysia. Analisis data terhadap ujian masa telah dijalankan menggunakan analisis varians dan teknik regresi untuk meneliti tahap signifikan pemboleh ubah dan menghasilkan persamaan ramalan untuk setiap elemen masa kerja, produktiviti setiap jam dan kos unit. Hasil kajian menunjukkan bahawa operasi pembalakan menggunakan RIMBAKA ini mampu mengeluarkan balak sebanyak 3.55 m^3 untuk satu kitaran dan mempunyai kadar penggunaan mesin sebanyak 74%, dengan produktiviti mencapai 46.39 m^3 untuk setiap jam mesin yang produktif. Kos menggunakan penuai RIMBAKA ialah RM12.70 m^{-3}. Oleh itu, jentera penuai RIMBAKA mempunyai beberapa kelebihan berbanding mesin pengheret darat. Kadar pengeluaran hasil yang lebih tinggi dengan penggunaan RIMBAKA akan dapat mengurangkan kos operasi.

INTRODUCTION

In Peninsular Malaysia, permanent forest estates is managed using the selective management system (SMS). SMS entails the selection of optimum felling regimes based on pre-felling inventory data and the cutting cycle is 30 years. Currently, forest harvesting has become more complex with the expansion of rules and regulations, adoption of international certification and more competitive wood products in the market. The trend towards increased mechanisation became widespread with primary emphasis on controlling cost, increasing timber productivity and safety, maintaining ecosystem balance and achieving high capital efficiency (Wester & Eliasson 2003). Productivity of timber extraction work is an important indicator for evaluating the efficiency of mechanised timber harvesting system. Introduction of new or modification of current harvester machine or system requires an evaluation of its productivity under the variable work conditions in the forest.

The system production rate is often measured on an hourly, daily or weekly basis. Timber load or volume is an indicator of the production

---

*Author for correspondence. E-mail: mhasmadi@putra.upm.edu.my

rate. Effective working time, flexibility and ease of use to the end-user were taken into account in calculation and analysis of machinery cost (Edwards et al. 2002, Parsakhoo et al. 2009). Accordingly, productivity of various machines has been studied during logging operations to evaluate elemental times and hourly productivity of feller-bunchers, harvesters, skidders and forwarders (Greene & McNeel 1991, Tufts & Brinker 1993a, b, Bavaghar et al. 2010).

In Malaysia, the practice of ground-based harvesting system using winch-equipped crawler tractor has been long recognised. Skidding logs from felling site to the landing area is one of the most important elements in timber extraction. The use of rubber-tyre skidders or crawler tractors often increase soil disturbance on forest roads or skid trails. The extraction and skidding task carried out by crawler tractor deplete residual stands of young trees and seedlings and create physical soil disturbances on forest floor due to compaction (Kennard et al. 2002, Grace et al. 2006). Soil disturbance due to skidding alters nutrient availability and remove the organic matter from forest floor, resulting in a considerable reduction in regeneration and growth of trees (Agherkakli et al. 2010). In the long term, this can have negative consequences on forest management.

In the early 1990s, reduced impact logging (RIL) was carried out in some forest areas in Peninsular Malaysia. In 2001, RIMBAKA R2020-A Timber Harvester (RIMBAKA harvester) was introduced. The RIMBAKA harvester was mainly deployed to skid logs from rocky and deep narrow corridors which were difficult and dangerous for crawler tractors. RIMBAKA harvester became the viable alternative to other reduced and low-impact technologies such as skyline, mobile tower yarder and helicopter, all of which were used since 1999. With the use of the environmentally-friendly RIMBAKA harvester, the use of crawler tractor was minimised.

RIMBAKA harvester system was independently designed and comprises the latest technology utilising two independent axial piston hydraulic motor with reduction. The 'logfisher' winch system was effective for log skidding from the tree stump as far as 150 m. The boom and arm were reinforced and constructed from high tensile steel materials. The machine was able to withstand repeated log hauling, excavation and lifting works. The arm which also acts as a pivot during the hauling process is fitted with a heavy duty bucket to perform digging operation and combines with a pair of grappler to load and stack logs (Figure 1).

Profit in timber production relies on cost-efficient harvesting operation (Efthymiou 2001). Harvesting productivity and effects of different variables on production efficiency are important indicators of any new machinery. Currently studies on the operational efficiency of RIMBAKA harvester in Peninsular Malaysia are limited. Therefore, the objective of this study was to evaluate the productivity and cost of timber extraction and the working pattern of the RIMBAKA harvester.

Figure 1 RIMBAKA R2020-A Timber Harvester

MATERIALS AND METHODS

Study site, data collection and analyses

Field trials were established in compartment 484-A Ulu Jelai Forest Reserve, Pahang, Peninsular Malaysia (Figure 2). The area is located at about 101° 36' E and 4° 19' N. Elevation is 60–880 m above sea level with maximum slope of 41°. Annual precipitation is between 150 and 200 mm and minimum temperature is 15.5 °C while maximum, 24.4 °C. The total area of the compartment is 71 ha and about 4703.4 m^3 of tress are allowed to be extracted. Logging is still on-going in the area. Logs harvested are mainly dipterocarps, namely, *Shorea leprosula, S. parvifolia* and *S. curtisii.*

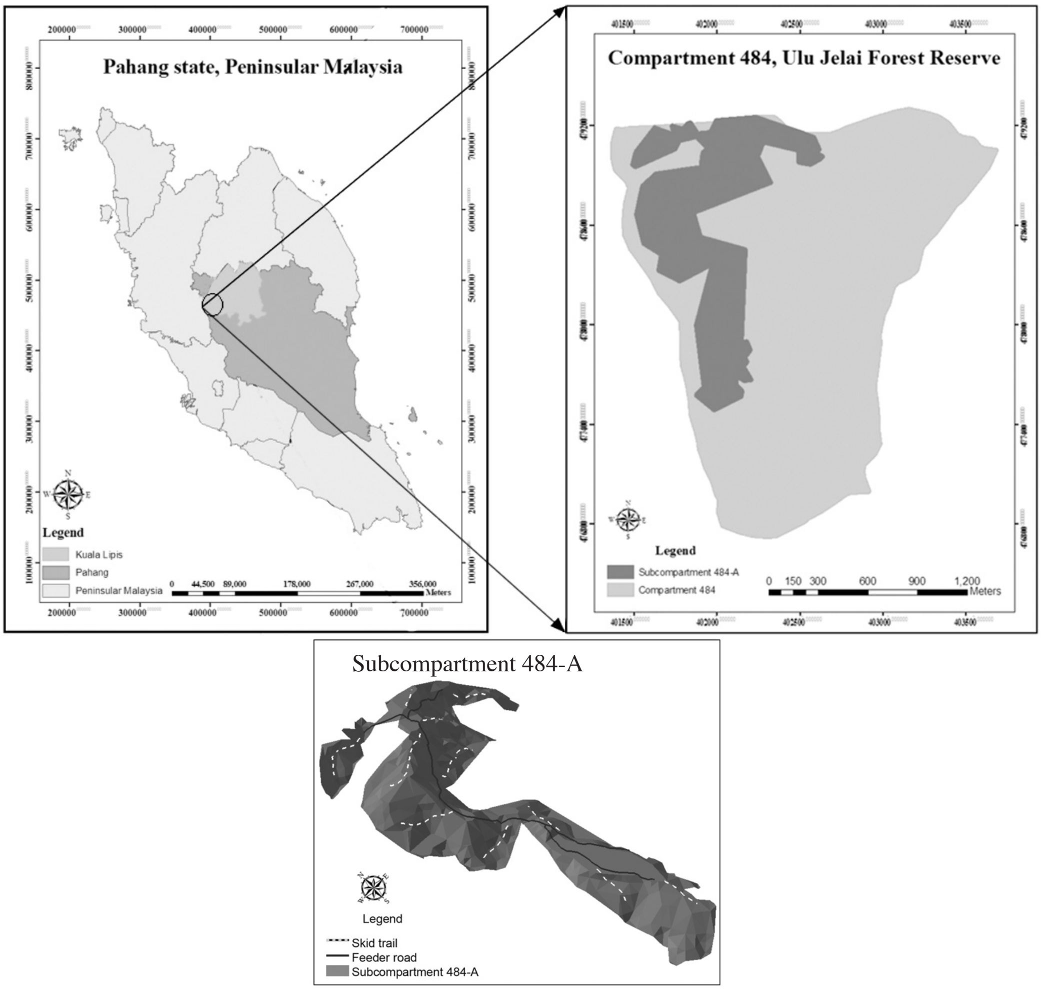

Figure 2 Study area of compartment 484-A in Ulu Jelai Forest Reserve, Kuala Lipis, Pahang, Peninsular Malaysia

Analyses of production and costs were limited to timber extraction and consist of unavoidable log cutting within the RIMBAKA harvester operation. Log loading and transport functions were not included in our analyses. The analyses were designed to ensure that inputs of labour and machines were restricted to the number of each necessary working element for a producing unit. Time-study method was used to assess the productivity of RIMBAKA. Total working time and each cycle time of elemental works were measured by means of electronic stop watches and digital camcorder. In total, we recorded the time duration for 48 extraction cycles. However, the number of each elemental work recorded varied depending on normal working procedures used to derive the production estimation (Table 1).

The determination of processing time on logs was analysed using multiple regression analysis (Bavaghar et al. 2010). The analysis was used for the purpose of selecting the best regression equation to predict the processing time (dependent variable: time) by the predictors (independent variables: skidding distance, skidding slope, hauling distance and skidded volume per turn). Distance and slope condition were recorded using hypsometer. Volume of skidded log (V) was calculated using the formula:

$$V = \pi r^2 h \qquad (1)$$

where $\pi = 3.142$, r = radius of log, h = length of log

Machine productivity and cost

Productivity of RIMBAKA harvester was estimated by dividing the volume of log extracted by the time per cycle and expressed in m^3/PMH

Table 1 Recording of time according to work element

Work element	Recording of time	
	Start	End
Travel empty	RIMBAKA harvester began to move from the current harvested stop (e.g. temporary logyard)	Machine reached feeder road side
Releasing winch	RIMBAKA harvester released its winch to the felled tree	Chokers reached the end of felled tree
Hooking	Chokers attached to the end of felled tree	Just before hauling
Hauling (winching)	Winch began to haul the felled tree	After the tree/log was placed at feeder road or temporary logyard
Unhooking	Unleashing of chokers from the end of the felled tree	When the chokers were released from tree and the winch was rolled
Tree cutting	Harvested trees were cut to logs using chainsaw	At the last cut
Travel loaded (skidding)	RIMBAKA harvester grappled the log and moved to temporary logyard	Grapple was released
Unloaded/sorting	RIMBAKA harvester placed/sorted the log at temporary logyard	RIMBAKA began to move to the next felled tree

and m^3/SMH (where PMH meant productive machine hour and SMH, scheduled machine hour). Machine rate of RIMBAKA harvester operation was obtained from interviews with the machine operator and his assistants and expressed in Ringgit Malaysia (RM) as shown in Table 2. The RIMBAKA unit cost was calculated as described by FAO (1992). Costs of operator and assistant wages and fuel consumption for RIMBAKA operations were included in the calculation for machine rates (Parsakhoo et al. 2009). When log cutting was required on slopes because the volume of harvested tree was too large to be extracted in one cycle, costs of chainsaw–man wages and chainsaw operation were included in the overall costs. The following formula was used for RIMBAKA productivity and cost study.

$$T = aN + b_1/x_1 + b_2/x_2 + [(b_3/x_3) + (b_4/x_3)] \quad (2)$$

where

T = sum of the times for travel empty, releasing winch, hooking, hauling and unhooking
a = combined time for hooking, unhooking and log sorting per log
N = number of log extracted
b_1 = minute per metre for travel empty
b_2 = minute per metre for loaded travel
b_3 = minute per metre for releasing winch
b_4 = minute per metre for hauling
x_1 = distance from landing to load pickup point
x_2 = distance from load pickup point to landing
x_3 = distance of winch released

The production rate (P) was calculated according to equation 3:

$$P = V/T \quad (3)$$

where V = volume per tree (m^3)

The unit cost (UC) of extraction by RIMBAKA was

$$UC = RE/P \quad (4)$$

where RE = machine rate for extraction

Therefore, cost estimation (C) for RIMBAKA harvester operation was calculated as in equation 5:

$$C\ (RM/SMH) = \text{Fixed cost} + \text{total variable cost} + \text{labour cost} \quad (5)$$

Table 2 Cost calculation for RIMBAKA harvester operation (including chainsaw operation)

Machine information	RIMBAKA	Chainsaw
Purchase price (RM)	750,000	4000
Salvage value (RM)	150,000	800
Life in years (year)	10	2
Scheduled hour/year (SMH)	1589	1589
Repair and maintenance (%/depreciation)	80	80
Labour fringe benefit factor (%)	30	30
Expected utilisation (%)	70	70

1RM = USD0.314

RESULTS AND DISCUSSION

Variations of time elements

The descriptive statistics of RIMBAKA harvester operations are presented in Table 3. The maximum and minimum total time values required for RIMBAKA harvester to accomplish one cycle of productive extraction activity were 0.24 and 0.02 hours respectively (Table 3). Similarly, gross productive times per working cycle were 0.29 and 0.03 hours respectively. This total time included log cutting which was 5.17 min and delay time of 1.42 min.

Average gross productive time per RIMBAKA harvester working cycle was 16.58 min, where 74% was elemental time and the rest, related to various kinds of delays (Table 3). This value was unfavourable when compared with values from conventional ground-based skidder operation at the Ulu Muda Forest Reserve (gross time 14.58 min, elemental time 92%) in Baling, Kedah, Peninsular Malaysia (Saharudin et al. 2004). Low percentage of utilisation in this study might be due to the differing cycle time per log extracted (Kellog & Bettinger 1994) as shown in the elemental time of log cutting, which was 23% of the working cycle. Log cutting element was included in RIMBAKA harvester operations to speed up hauling process as well as increase productivity. Total log volume of log extracted showed variations to cycle time (Spinelli et al. 2002a, Wang & Haarlaa 2002). The lower the volume of log hauled per working cycle, the faster the haul speed. Maximum haul speed was 3.43 m min^{-1} with minimum delay observed at only 4%. The most time-consuming element in this study was hauling. Terrain variations seemed to be the reasons for high proportion of recorded time, i.e. 26%. Rough terrain is not passable to harvesting machines (Stampfer 1999, Stampfer & Steinmuller 2001). For example, in this study, undulating slope surface made the hauled log stuck and friction between hauled log and residual stands along hauling path reduced the haul speed.

Miscellaneous delay times observed in this study included time to find the suitable position for RIMBAKA harvester to release the winch wire. They also included time to find the path to reach felled trees to be hauled without damaging residual stands and avoiding lianas. Likewise, during hooking process, more time was required when a tree fell parallel to the slope. The RIMBAKA harvester operator assistant had to dig the soil beneath the end of the log to hook the winch wire and start the hauling. In this study, approximately 22% of log cutting interference was recorded in the extraction process. Mechanical delay due to engine breakdown and boggy chain problems of RIMBAKA harvester did not occur since this machinery was periodically maintained and inspected regularly before operation began. Maintaining the safety of machine benefits production rate (Owende et al. 2002).

RIMBAKA harvester productivity

Results showed that production rate was 46.39 m^3/PMH and 31.92 m^3/SMH (Table 3). The production rate appeared slightly higher compared with conventional ground-based harvesting where the productivity values were 45.98 m^3/PMH and 42.50 m^3/SMH (Saharudin et al. 2004).

Table 3 Descriptive statistics of RIMBAKA harvester operation

Item	N	Min	Max	Mean	SD
Variable					
Skidding distance (m)	48	5	77	25.92	11.52
Hauling distance (m)	35	14	78	35.72	18.05
Volume (m^3)	48	1.6	11.01	3.55	1.68
Slope (°)	48	22	38.3	30.94	4.20
Elemental time (min)					
Travel empty	48	0.16	3.58	0.92	0.69
Releasing winch	35	0.2	1.17	0.55	0.25
Hooking and unhooking	35	0.29	1.51	0.89	0.35
Hauling	35	1	7.48	3.02	1.42
Skidding (travel loaded)	48	0.08	2.58	0.90	0.56
Log cutting	43	0.59	5.17	1.98	0.99
Delay	35	0.01	1.42	0.42	0.34
Sorting	48	0.25	2.00	0.89	0.40
Element measured					
Total productive time (hour)	48	0.02	0.24	0.10	0.05
Gross productive time (hour)	48	0.03	0.29	0.14	0.06
Productive machine hour (m^3/PMH)	48	11.17	129.32	46.39	29.85
Gross machine hour (m^3/SMH)	48	8.22	89.45	31.92	18.02
Unit cost (RM/m^3)	48	2.38	38.40	12.70	7.30

N = Total number of variables; Min = minimum, Max = maximum; SD = standard deviation

This study disclosed that the production rate had been influenced by predictive variables measured, namely, volume, skidding distance, hauling distance and slope (Figures 3–6 respectively). Time and productivity varied roughly in a linear manner with log size (Nakagawa et al. 2008). There were positive relationships between production rate and volume extracted where the production rate increased when volume increased (Figure 3). This result was consistent with findings by Jirousek et al. (2007) who used a forwarder in clear cutting operation. High log volume extracted will give high return in RIMBAKA harvester operation. The machine was capable of hauling up to 1000 kg log per cycle and thus, reduced the time required for extraction of log compared with conventional ground-based machinery. In the case where hauling and skidding distance increased, the production rate decreased accordingly (Figures 4 and 5). The results were similar to the study by Behjou et al. (2008), where skidding distance had primary effect on the production rate, besides hauling distance and slope condition. Since RIMBAKA harvester performed at hill forest with maximum elevation of 880 m above sea level, undulating slope condition was a major constraint in its working cycle. In this study, haul speed decreased when slope increased and subsequently the productivity decreased too (Figure 6). Cycle time decreased as slope increased and skidding was carried out in a downhill direction (Ghaffarian et al. 2007). Higher speed travel with load consequently increased the production rate of forwarder used.

Table 4 shows the relationship between predictive variables and cycle productive time and cycle gross time through regression analysis. The stepwise analysis showed significant effects of productivity to cycle time ($\alpha < 0.05$).

Productivity had significant effect to volume of log extracted and skidding distance, both in productive and gross times. Volume and skidding distance affect cycle time and have been used effectively in predictive equations of machinery productivity (Spinelli et al. 2002b). However, Spinelli and Magagnotti (2010) discarded volume and skidding distance in their regression analysis because both variables showed little variation to working cycle time.

It was also found that hauling distance had significant influence on productive working time

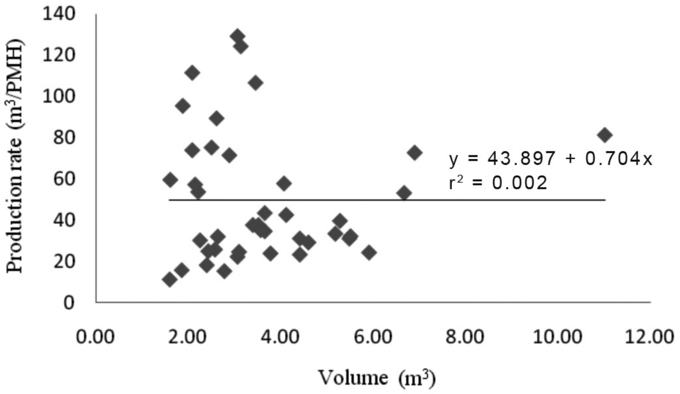

Figure 3 Relationship between production rate and log volume of RIMBAKA harvester; PMH = productive machine hour

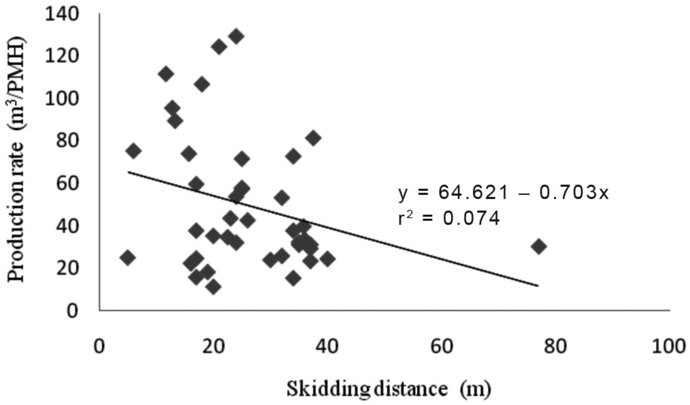

Figure 4 Relationship between production rate and skidding distance of RIMBAKA harvester; PMH = productive machine hour

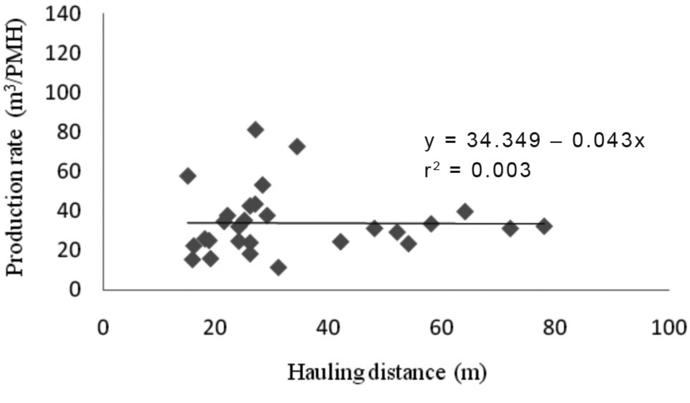

Figure 5 Relationship between production rate and hauling distance of RIMBAKA harvester; PMH = productive machine hour

of RIMBAKA harvester operation but there was no variation in gross working time. This was probably due to residual stand composition and adverse slope condition along hauling path that required extra time for log hauling. Such obstacles that occurred along travel track made travel speed low. Log was sometimes stuck at undulated slope surface, or speed of hauling reduced due to friction between contact surface of hauled log and residual stands or lianas along the hauling path. Irregularity in extra time consumption per cycle (recorded in the delay time) could be the

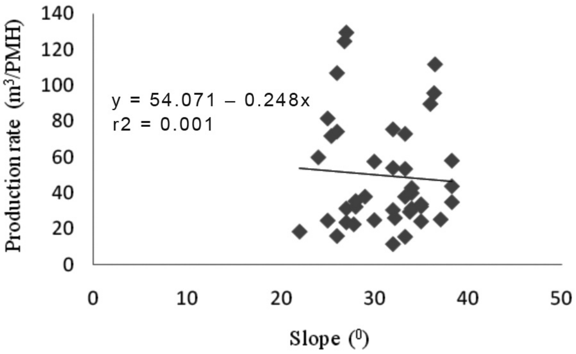

Figure 6 Relationship between production rate and slope of RIMBAKA harvester; PMH = productive machine hour

Table 4 Linear regression analysis of predicted variables as a function of cycle time

Dependent variable	y-Intercept	Regression coefficient	r^2	Significance ($\alpha < 0.05$)
		Total productive time (PMH)		
Volume (m^3)	0.048	0.015	0.472	0.01
Skidding distance (m)	0.048	0.02	0.193	0.02
Hauling distance (m)	0.093	0.01	0.198	0.01
Slope (°)	0.112	0.00001	0.001	0.84*
		Gross productive time (SMH)		
Volume (m^3)	0.079	0.016	0.17	0.004
Skidding distance (m)	0.076	0.002	0.168	0.004
Hauling distance (m)	0.149	0.0004	0.038	0.263*
Slope (°)	0.132	0.0001	0.0005	0.959*

*Not significant at $\alpha < 0.05$

reason for the insignificant relationship between hauling distance and SMH. Slopes did not show any variation to RIMBAKA harvester operations; thus, slope variable was discarded from stepwise regression analysis. During the hauling process, the end front of the log was raised off the ground and less friction occurred between the log and slope surface, subsequently making the winch operate smoothly. Cable yarding system was a desirable practice to extract log at rugged and steep slope condition (Visser et al. 2009). Accordingly, the 'logfisher' system of RIMBAKA harvester operation by winch wire attached to the mounted rear end of boom may perhaps explain the non-significant effects of slope towards cycle time in this study. The significant residual mean square value derived from those variables could be effectively used to estimate productivity of the RIMBAKA harvester. The stepwise analysis of volume, skidding distance and hauling distance to productive cycle time showed that the predictive equation was primarily affected by skidding distance. The estimated equation derived for productivity of RIMBAKA harvester as a function of skidding distance (m) without any delay can be described as:

$$P \text{ (hour)} = 0.061 + 0.02_{\text{skidding distance}} \qquad (9)$$
$$r^2 = 0.275$$

Equation 9 explained 28% of the productivity variability through hauling distance variables and the predictive equation was significant at $\alpha < 0.05$. In the estimation of gross working cycle productivity, hauling distance and slope were not used in the regression equation because they were not significant ($\alpha < 0.05$). Volume and skidding distance showed positive association with gross working cycle but only log volume was used to estimate productivity as it had significant effect on residual mean square. The estimated predictive equation on the basis of gross working cycle was determined by equation 10 which explained 17% of the variation:

$$P \text{ (hour)} = 0.079 + 0.016_{\text{volume}} \qquad (10)$$
$$r^2 = 0.170$$

The production equation derived from this study will be useful in predicting productivity when RIMBAKA harvester is used in other similar forest management units. Both productivity equations derived from observed productive cycle time (equation 9) and gross cycle time (equation 10) had significant effects at $\alpha = 0.05$. The range of r^2 value described the effectiveness of equations in predicting productivity of the RIMBAKA harvester. However, low validity of r^2 value of these equations may limit the usage of the machine at stream forest stand area. A validation of r^2 value from future studies of RIMBAKA harvester productivity at different forest stands and terrain conditions will give variability of the outcomes derived with different predictive variables.

The nature of working operation in hilly forest with undulating topographic condition and first harvesting cycle is unpredictable. In this study, RIMBAKA harvester was able to operate on slopes steeper than suggested (> 40°). The density of logs in the study compartment was about 67 $m^3 ha^{-1}$ and 38.04 $m^3 ha^{-1}$ of trees were allowed to be extracted based on pre-felling inventory. Since felling was pre-aligned towards forest road, the extraction process was completed in a shorter time and, thus, productivity of RIMBAKA harvester operation was optimised and cost of skidding reduced. Since skid trails were not created in this operation area, the feller and RIMBAKA harvester's assistant had to ensure the best direction the tree should be felled in order to make the winch wire reachable. Forest operational plan map was referred to assist the machine operator to park the RIMBAKA harvester at a suitable ridge point. When the winch wire was not able to attain the desired log, the hauling path was adjusted accordingly by minimising terrain variables constraints.

Machinery cost

Machine rate was determined for RIMBAKA harvester and chainsaw operations including labour cost. The prerequisite conditions for fuel, tyres and tracks and labour rate calculation are shown in Table 5. The labour was paid monthly by forest concessionaire, and hourly labour cost was based on standard monthly wages for each worker. In a month, there were roughly 20 working days and the scheduled working hour was 7 hours per day, lunch break intervals excluded.

When chainsaw had to be used in extraction process together with RIMBAKA harvester, the cost went up to RM315.81/SMH compared with RM213.17/SMH when using RIMBAKA harvester alone. Labour cost for operator and assistant when using RIMBAKA harvester was RM53.56/SMH. If chainsaw was used together with RIMBAKA harvester, labour cost went up 57% to reach RM124.99/SMH.

This study revealed that total cost of extraction was RM12.70 m^{-3}. This cost was 26.8% higher than conventional ground-based harvesting which was only RM9.30 m^{-3} (Saharudin et al. 2004). High performance and technological improvements of RIMBAKA harvester towards RIL increased cost in investment. The same finding was reported by

Table 5 Prerequisite condition required for machine rate calculation

Costing factor	RIMBAKA		Chainsaw
	Operator	Assistant	Operator
Wage (RM)*	6000	1500	10,000
Labour rate (RM/SMH)	42.86	10.70	71.43
Fuel tank capacity (L)	450		0.5
Fuel usage (L)	286		2
Fuel price (RM/SMH)**	71.5		0.50
Maintenance (RM)*	8000 (tyre and tracks)		3000 (chain bar)
Maintenance price (RM/SMH)	57		21.43

*Costs estimated by forest concessionaire per month, **cost according to current fuel price (RM1.75 L^{-1}); SMH = scheduled machine hour; 1RM = USD0.314

Abdul Rahim et al. (2009) who experienced an increase of 57.4% in cost when practicing RIL. A crawler tractor cost for skidding process was only RM0.58 m^{-3} (Saharudin et al. 2004) and increased to RM5 m^{-3} with RIMBAKA harvester. High fuel tank capacity and maintenance of RIMBAKA harvester instruments such as bogie tracks, winch drum and winch wire contributed to the cost. However, harvesting operation and investments costs by new machine can be recovered when the machine or equipment operates efficiently (Akay et al. 2004).

CONCLUSIONS

On average, RIMBAKA harvester extracted 3.55 m^3 logs per cycle and the rate of machine utilisation was 74%. Productivity rate when using RIMBAKA harvester was 46.39 m^3/PMH. Thus, the machine cost of RIMBAKA harvester (including chainsaw) was RM12.70 m^{-3}. RIMBAKA harvester system had some advantages over ground-based skidders which included increased productivity, reduced delay time (without log cutting element) and higher efficiency in log skidding even on steep slope and long hauling distance. However, the cost of RIMBAKA harvester operation was much higher than conventional ground-based skidder. Nevertheless, with the higher productivity rate of RIMBAKA harvester system, the cost of operation can be reduced. In future studies, it is recommended to include the operational efficiency and costing factor of the whole timber harvest activities by RIMBAKA harvester to strengthen the predictive equation derived, while cost constraints assumption can be verified according to the best management practice.

ACKNOWLEDGEMENTS

We convey special thanks to O Rahim, M Ramli and the staff of the forestry company of Syarikat Upayapadu Sdn Bhd for their assistance in both organising and carrying out this work. This research was funded by the Malaysia government through the Research University Grant Scheme.

REFERENCES

Abdul Rahim AS, Mohd Shawahid O & Zariyawati MA. 2009. A comparison analysis of logging cost between conventional and reduced impact logging practices. *International Journal of Economic and Management* 3: 354–366.

Agherkakli B, Najafi A & Sadeghi SH. 2010. Ground-based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. *Journal of Forest Science* 56: 278–284.

Akay AE, Erdas O & Sessions J. 2004. Determining productivity of mechanised harvesting machines. *Journal of Applied Science* 4: 100–105.

Bavaghar MP, Sobhani H, Feghhi J, Darvishsefat AA & Mohajer MRM. 2010. Comprehensive productivity models for tracked and wheeled skidders in the Hyrcanian forests of Iran. *Journal of Forest Research* 4: 65–71.

Behjou FK, Majnounian B, Namiranian M & Dvorak J. 2008. Time study and skidding capacity of the wheeled skidder Timberjack 450C in Caspian forests. *Journal of Forest Science* 54: 183–188.

Edwards DJ, Holt GD & Harris FC. 2002. Predicting downtime costs of tracked hydraulic excavator operating in the UK opencast mining industry. *Construction Management Economics* 20: 581–591.

Efthymiou PN. 2001. Efficiency problems in harvesting small-dimensioned wood. Paper presented at the FAO/ILO Seminar on New Trends in Wood Harvesting with Cable Systems for Sustainable Forest Management in Mountains. 9–22 June 2001, Ossiach.

FAO. 1992. *Cost Control in Forest Harvesting and Road Construction*. FAO Forestry Paper 99. Food and Agricultural Organization of United Nation, Rome.

Ghaffarian MR, Stampfer K & Session J. 2007. Forwarding productivity in southern Austria. *Croatian Journal of Forest Engineering* 28: 169–175.

Grace JMI, Skaggs RW & Cassel DK. 2006. Soil physical changes associated with forest harvesting operations on an organic soil. *Soil Science Society America Journal* 70: 503–507.

Greene WD & McNeel JF. 1991. Productivity and cost of sawhead feller-bunchers in the South. *Forest Products Journal* 41: 21–26.

Jirousek R, Klvac R & Skoupy A. 2007. Productivity and costs of the mechanized cut-to-length wood harvesting system in clear felling operations. *Journal of Forest Science* 53: 476–482.

Kellog LD & Bettinger P. 1994. Thinning productivity and cost for mechanized cut-to-length system in the northwest Pacific coast region of the USA. *Journal of Forest Engineering* 5: 43–52.

Kennard DK, Gould K, Putz FE, Fredericksen TS & Morales F. 2002. Effect of disturbance intensity on regeneration mechanisms in a tropical dry forest. *Forest Ecology and Management* 162: 197–208.

Nakagawa M, Hamatsu J, Saitou T & Ishida H. 2008. Effects of tree size on productivity and time required for work elements in selective thinning by a harvester. *Journal of Forest Engineering* 18: 43–48.

Owende PMO, Lyons J & Ward SM. 2002. Operations protocol for eco-efficient wood harvesting on sensitive sites. The Ecowood Project, Contract No. QLK5-1999-00991(1999–2002). http://www.ucd.ie/foresteng/html/ecowood /op.pdf.

Parsakhoo A, Hosseini SA, Lotfalian M & Jalilvand H. 2009. Efficiency and cost analysis of forestry machinery usage in Hyrcanian Forests of Iran. *World Applied Science Journal* 6: 227–233.

Saharudin A, Azmi H & Mohd-Zamri R. 2004. *Kajian Mengenai Kos dan Produktiviti Sistem Pengusahasilan Hutan Bukit di Semenanjung Malaysia.* Jabatan Perhutanan Semenanjung Malaysia, Kuala Lumpur. (In Malay)

Spinelli R, Hartsough BR, Phili MOO & Shane MW. 2002a. Productivity and cost of mechanized whole-tree harvesting of fast growing eucalypt stands. *Journal of Forest Engineering* 13: 34–44.

Spinelli R, Philip MOO & Shane MW. 2002b. Productivity and cost of CTL harvesting of *Eucalyptus globulus* stands using excavator-based harvester. *Forest Products Journal* 52: 67–77.

Spinelli R & Magagnotti N. 2010. Performance and cost of a new mini-forwarder for use in thinning operations. *Journal Forestry Research* 15: 358–364.

Stampfer K. 1999. Influence if terrain conditions and thinning regimes on productivity of a track-based steep slope harvester. *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium.* 28 March–1 April 1999, Corvallis.

Stampfer K & Steinmuller T. 2001. A new approach to derive a productivity model for the harvester 'Valmet 911 Snake'. Paper presented at the International Mountain Logging and 11th Pacific Northwest Skyline Symposium. 10–12 December 2001, Seattle.

Tufts RA & Brinker RW. 1993a. Valmet's woodstar series harvesting system: a case study. *Southern Journal of Applied Forestry* 17: 69–74.

Tufts RA & Brinker RW. 1993b. Productivity of a Scandinavian cut-to-length system while second thinning pine plantations. *Forest Products Journal* 43: 24–32.

Visser R, Spinelli R, Saathof J & Fairbrother S. 2009. Finding the 'Sweet-Spot' of mechanised felling machines. The 32nd Annual Meeting of the Council on Forest Engineering. 15–18 June 2009, Kings Beach.

Wang J & Haarlaa R. 2002. Production analysis of an excavator-based harvester: a case study in Finnish forest operation. *Forest Products Journal* 52: 85–90.

Wester F & Eliasson L. 2003. Productivity in final felling and thinning for a combined harvester-forwarder (Harwarder). *International Journal of Forest Engineering* 14: 45–50.