Yarding productivity of tree-length harvesting using a small cable-yarder in steep slope, South Korea

Minjae Cho, Koohyun Cho, Byoungkoo Choi and Dusong Cha

ABSTRACT

Tree diameter, topography, and stand accessibility have been major issues to consider when selecting the optimal equipment to extract logs from steep slopes. With an increasing interest using cable logging systems from steep slopes in South Korea, the yarding productivity and cost were evaluated for a small scale cable yarder. A standard time and motions study method were applied for three clearcut units in larch (Larix kaempferi) stands located in Pyeongan, Gogil, and Ungyo in Eastern Gangwon of South Korea. The average yarding productivity and cost were calculated at 5.7 m³/scheduled machine hour (SMH) and $27.9/m³, respectively. The regression analysis reveals that the mean diameter class was found to have greatly influenced yarding productivity. Among the factors determining the yarding cost, tree volume was found to have the greatest influence, followed by lateral distance and yarding distance. Other factors that may contribute to reducing delay and improving yarding productivity included operational planning (i.e. corridor layout considering topographic conditions), pre-inspection, and post-maintenance/management of the yarder system, and specialized technical training to enhance yarding productivity.

Introduction

Due to the success of the government-led national afforestation project in the 1970s, >70% of the forests in South Korea have stand age classes III or IV, or over, reaching the large-diameter timber harvesting stage. Currently, the Korea Forest Service has been pursuing forest management practices enhancing domestic log production with the view to increasing the timber self-sufficiency rate from 66% as of 2015 to 21% by 2020 (Korea Forest Service 2016). However, timber harvesting is a dangerous and labor-intensive occupation, as it involves felling trees and processing them into logs on steep terrain and transporting them to purchasers, workers tend to use mechanized systems on steep grounds. Further, due to the difficulties in recruiting forestry workforce, such sites suffer from a shortage of new workers and an aging workforce. In addition, the discrepancy between rising wages and input prices and stagnating timber prices is worsening the economic feasibility of timber harvesting. In order to increase the economic feasibility of timber harvesting operations under these circumstances, it is essential to improve the production infrastructure (i.e., forest roads) and mechanize forest operations.

In South Korea, a grapple mounted on an excavator-based machine performs most of the timber harvesting operations. This method has high-harvesting productivity because it does not require a specialized forestry worker familiar with the low-cost equipment and can be performed by any on-site worker, who only has to collect the timber. However, the current harvesting practices have resulted in various kinds of negative impacts such as soil compaction and soil displacement (Han and Kellogg 2000; Kolka et al. 2012; Solgi and Najafi 2014).

To address this issue and ensure sustainable and efficient timber harvesting practices, the Korea Forest Service has distributed high-performance forestry equipment such as imported long-distance skyline yarders (tower yarder) to timber harvest sites, and has developed and distributed yarders capable of mid- and short-distance cable yarding (Korea Forest Service 2016). However, imported long-distance skyline yarders require high initial investment for purchase and high maintenance/management costs. In addition, their large size is poorly suited for narrow forest roads, in South Korea making it difficult to secure enough space for efficient operation, and takes an unusually long time to set up. To solve this problem, a small (height in 7.3 m) tower yarder (HAM300) was domestically developed in 2014 as a long-distance cable yarding system tailored to Korea’s forest structures and forest road conditions. Currently, basic data on its productivity and cost are being gathered, as well as its operational performance is being evaluated.

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Studies on yarding operations using cable system include Woo et al. (1990) study of the costs of cable yarding operation and mechanical yarding operation using a small cable crane (K-300), followed by studies on yarding operations using Chuncheon yarder, swing yarder, and tower yarders (Han et al. 2008; Kim and Park 2012; Lee and Oh 2013; Cho et al. 2014, 2015). In other countries, Brown and Kellogg (1996) performed an economic feasibility analysis of yarding operations using tower yarders to reduce fuel cost of transportation, improve the conditions for tree growth, and minimize soil damage. Hartley and Han (2007) estimated the yarding productivity and cost of four different types (clearcut, two-age, patch cut and thin, and group selection) of yarding operations using swing yarder (Washington 78SL), and developed regression equations for yarding operation productivity.

There were many cable yarding productivity and cost analyses of operations using cable yarding systems used in South Korea. For example, You (2015) and Cho et al. (2016) performed productivity and cost analyses in their studies on yarding operations using HAM300, a domestic tower yarder in its early development stage. Although we have done several cable yarding studies in South Korea, there has been little research conducted to develop a yarding productivity regression equation.

Therefore, this study was conducted to estimate the productivity and cost of the domestically developed HAM300 and to develop a yarding productivity regression equation for predicting yarding productivity in an effort to provide basic data for establishing an efficient timber harvesting system.

Materials and methods

Study area

The sites selected for the study were four clearcut sites consisting of mainly larch trees located in Pyeongan, Gogil, and Ungyo in Pyeongchang, Korea where uphill yarding with a HAM300 was performed for tree-length harvesting system. The average diameter at breast height (DBH) of larch (Larix kaempferi) in the study sites was 34 cm and average slope was 39% (Table 1). These sites were harvested in different periods, however, close in stand age and stand conditions.

Table 1. Stand description and work conditions of the study area

| Item                        | A    | B    | C    | D    | Total |
|-----------------------------|------|------|------|------|-------|
| Year                        | 2014 | 2015 | 2016 |      |       |
| Location                    | Pyeongan | Gogil | Ungyo |      |       |
| Type                        | Coniferous forest |        |      |       |       |
| Species                     | Larch (Larix kaempferi) |      |      |       |       |
| Area (ha)                   | 0.4  | 0.2  | 1.4  | 0.7  |       |
| Age (year)                  | 52   | 55   | 51   |      |       |
| Average tree height (m)     | 22   | 26   | 23   | 23   |       |
| Average DBH (cm)            | 32   | 37   | 34   |      |       |

*Values in parentheses indicate the range of tree height and DBH.

Yarding operations

A four-man crew consisting of a one-yarder operator and three chokermen performed yarding operations using a HAM300. Specifications of the tower yarder a HAM300 used are as follows: the maximum yarding distance was 300 m, tower height range was 2.6 to 7.3 m, the mass was 1850 kg, and horse power was 80–100 hp. Table 2 provides an overview of the yarding operations conducted in each of the study sites.

Table 2. Yardage description of the study area.

| Item                        | A    | B    | C    | D    | Total |
|-----------------------------|------|------|------|------|-------|
| Number of yarding cycles    | 37   | 45   | 45   | 108  | 235   |
| Average yarding distance (m)| 78   | 33   | 97   | 89   | 78    |
| (35 ~ 127)*                 |      |      |      |      |       |
| Average lateral distance (m)| 6   | 9   | 8   | 9   | 9     |
| (0 ~ 17)                    |      |      |      |      |       |
| tree volume (m³/cycle)      | 0.85 | 1.00 | 1.11 | 0.84 | 0.92  |

*Values in parentheses indicate the range of yarding distance and lateral distance.
delays (Han 2008; Cho 2015). Yarding productivity (m3/hr) was calculated on the basis of production rate (number of log/hr) and average log volume (m3/log). The production rate was calculated by averaging the measured continuous working hours, and the timber volume was calculated using the Smalian equation (Kim 2008). In addition, delays and yarding productivity depending on the machine utilization rate were analyzed for improving yarding productivity.

**Machine cost**

Machine cost was calculated for a total of the fixed, operating, and labor costs using the machine rate method (Miyata 1980; Brinker et al. 2002). The fixed cost includes depreciation expense, interest, insurance, and taxes, irrespective of the machine’s operational status (on or off mode). The operating cost includes expenses concerning the machine operation, such as fuel, lubricant, and repair/maintenance cost. The labor cost was calculated in three categories: direct wages, indirect wages, and benefits. The costs of individual factors for the calculation of the machine cost are presented in Table 3.

**Table 3. Cost factors and assumptions used for machine rate calculations**

| Cost factor          | Unit | A   | B   | C   | D   |
|----------------------|------|-----|-----|-----|-----|
| Purchase price       | $    | 83,636 |     |     |     |
| Economic life        | years | 7   |     |     |     |
| Salvage value        | %    | 10  |     |     |     |
| SMH* hours/year      |      | 300 |     |     |     |
| Annual interest rate | %    | 17  |     |     |     |
| Repair and maintenance | %  | 100 |     |     |     |
| Oil price $/liter    |      | 1.39 | 1.19 | 1.05 | 1.05 |
| Coefficient of lubricant | %  | 37  |     |     |     |
| Fuel consumption $/liter/hr |      | 7   |     |     |     |
| Daily wage of operator $/day |      | 96.88 | 98.40 | 104.79 | 104.79 |
| Daily wage of ground crew $/day-person |      | 78.81 | 79.82 | 85.76 | 85.76 |

*SMH means scheduled machine hours.

Yarding productivity regression equation

In a tree-length harvesting system comprising felling and delimbing in the harvesting site, yarding to the roadside landing, and processing, the yarding operation makes up the greatest portion. In order to analyze the influence of yarding operations on tree-length harvesting system, a yarding productivity regression equation was developed in this study. Lateral distance, yarding distance, and tree volume were used as predictor variables for the yarding productivity regression equation. To validate the model equation, a first model equation was developed using about 70% of the data, and a t-test analysis of the predicted and measured values was performed with the remaining about 30% (Snee 1977; Adebayo et al. 2007). The following t-statistics was used for the t-test.

\[ t' = \frac{D}{S_{D}} \]  

\[ t' = t\text{-statistics.} \]

When a yarding productivity regression equation was a good fit to represent the given data, the final yarding productivity regression equation was established using the full data (Shin and Han 2006; Han 2008; Cho et al. 2016). Further, the influence of individual yarding cost factors was analyzed using the finally established yarding productivity regression equation along with the factors, lateral distance, yarding distance, and tree volume.

**Results and discussion**

**Yarding productivity**

The machine utilization rate for yarding operations was 57% based on the analysis of the all collected during our study period for all the study sites. The yarding productivity per hour was 5.7 m³/SMH, with that of individual study sites varying between 4.2 m³/SMH and 6.3 m³/SMH. The yarding productivity tended to be low in the initial years of equipment development and increases in proportion to the stability of equipment performance and task competence. The values calculated in this study were higher than those of the study by You (2015) for uphill yarding productivity using a HAM300. This difference in yarding productivity between the two studies appears to be ascribed to the difference in the mean diameter class; because, lateral distance, yarding distance, and the machine utilization rate were similar.

Given that yarding productivity and the machine utilization rate are positively correlated (Harrill and Han 2012), it is essential to increase the productive machine hour (i.e. the machine operating time) by minimizing the delay in the scheduled machine hour to increase the machine utilization. Earlier studies conducted in South Korea reported that the machine utilization rates of yarding operations using tower yarders (RME-300T, Koller K301-4) and swing yarders ranged between 60% and 80% (Kim and Park 2012; Cho et al. 2014; Cho et al. 2015). Those using tower yarder (Koller K300) and swing yarder in studies conducted in other countries range between 65 and 87% (Huyler and Ledoux 1997; Hartley and Han 2007). The delay analysis results for each study sites are outlined in Table 4. Delays for tower yarder’s setup and displacement were for the largest proportion with 9000 seconds. Most of the delays in the initial stage of equipment introduction were mechanical delays attributable to carriage battery changes, the breakdown of the carriage, and pressure regulation of carriage. Other operational delays due to inexperienced machine operation and choker handling, such as wires hang-up, waiting, and re-positioning of the carriage, also occupied a large proportion. Such operational delays were reduced, as the time for setup and displacement was reduced by efficient work-flow planning, such as corridor layout
optimized for the given topological conditions. Minimization of mechanical problems through pre-inspection and post-maintenance/management of the yarder system and improvement of task competence through professional skill training would also contribute to the increase of the machine utilization rates.

**Yarding cost**

The mean yarding cost of $27.91/m³ was obtained by analyzing all the data collected from all four study sites, with the lowest and highest values being $25.35/m³ and $36.52/m³ (Table 5). These results are lower than those calculated by You (2015) using a HAM300, but higher than those calculated in the studies using tower (RME-300T, Koller K301-4), swing yarder, and Chuncheon yarders (Han et al. 2008; Kim and Park 2012; Cho et al. 2014; Cho et al. 2015). This high-yarding cost was due to the low machine utilization rate of the domestically developed HAM300. This operational factor was reflected in the considerable differences between the lowest and highest machine utilization rates and yarding costs, ranging from 50 to 100% and $15.92/m³ to $31.83/m³, as shown in Table 6. This suggests that low-cost yarding operations can be achieved by raising the machine utilization rate to 80% or higher by enhancing task competence through management education and a targeted training of the specialized professional workforce.

### Analysis of yarding productivity

To analyze the influence of each of the elements of a yarding operation, a yarding productivity regression equation was developed and sensitivity analysis of each element was performed with respect to the yarding productivity and cost.

#### Yarding productivity regression equation

A regression equation was developed to estimate yarding productivity. The full dataset totaling 230 yarding cycle data were divided into two data groups of 152 and 78 data points to be used for the development of the preliminary regression equation and t-test, respectively. The preliminary yarding productivity regression equation included lateral distance, yarding distance, and tree volume variables (Table 7). The results of the t-test performed to confirm the good fit of the preliminary yarding productivity regression equation. Given that the difference between the measured and estimated values are not considered significant under a significance level of

| Site | Item | A | B | C | D | Total |
|------|------|---|---|---|---|-------|
| **Machine utilization (%)** | 50 | 49 | 61 | 63 | 57 |
| **Fixed costs ($/hr)** | 35.84 | 35.84 | 35.84 | 35.84 | 35.84 |
| Depreciation | 35.84 | 35.84 | 35.84 | 35.84 | 35.84 |
| Interest, insurance and tax | 25.69 | 25.69 | 25.69 | 25.69 | 25.69 |
| Operating costs ($/hr) | 8.65 | 8.65 | 7.35 | 7.35 | 7.35 |
| Fuel | 3.46 | 3.46 | 2.94 | 2.94 | 2.94 |
| Lube | 71.20 | 73.33 | 58.96 | 57.01 | 62.89 |
| Repair and maintenance | 41.66 | 42.23 | 45.26 | 45.26 | 45.26 |
| Labor costs ($/hr) | 4.54 | 4.60 | 5.39 | 5.39 | 5.39 |
| Labor | 4.42 | 4.48 | 4.95 | 4.95 | 4.95 |
| Insurance | 154.10 | 154.62 | 159.23 | 159.44 | 158.84 |
| Total machine costs ($/SMH) | 4.22 | 5.55 | 6.12 | 6.29 | 5.69 |
| Hourly productivity (m³/SMH) | 36.52 | 27.86 | 26.02 | 25.35 | 27.91 |

*Based on four-men crew.

$\text{Productivity} = \frac{\text{Machine utilization}}{100} \times \frac{\text{Yarding rate}}{\text{Machine costs}}$

Where:
- **Machine utilization (\%)**
- **Yarding rate ($/m³)**
- **Machine costs ($/SMH)**

### Table 5. Yarding cost in four different study sites.

| Study site | Item | A | B | C | D | Total |
|------------|------|---|---|---|---|-------|
| **Machine utilization (%)** | 50 | 49 | 61 | 63 | 57 |
| **Fixed costs ($/hr)** | 35.84 | 35.84 | 35.84 | 35.84 | 35.84 |
| Depreciation | 35.84 | 35.84 | 35.84 | 35.84 | 35.84 |
| Interest, insurance and tax | 25.69 | 25.69 | 25.69 | 25.69 | 25.69 |
| Operating costs ($/hr) | 8.65 | 8.65 | 7.35 | 7.35 | 7.35 |
| Fuel | 3.46 | 3.46 | 2.94 | 2.94 | 2.94 |
| Lube | 71.20 | 73.33 | 58.96 | 57.01 | 62.89 |
| Repair and maintenance | 41.66 | 42.23 | 45.26 | 45.26 | 45.26 |
| Labor costs ($/hr) | 4.54 | 4.60 | 5.39 | 5.39 | 5.39 |
| Labor | 4.42 | 4.48 | 4.95 | 4.95 | 4.95 |
| Insurance | 154.10 | 154.62 | 159.23 | 159.44 | 158.84 |
| Total machine costs ($/SMH) | 4.22 | 5.55 | 6.12 | 6.29 | 5.69 |
| Hourly productivity (m³/SMH) | 36.52 | 27.86 | 26.02 | 25.35 | 27.91 |

*Based on four-men crew.

### Table 6. Yarding costs estimated based on different machine utilization rates.

| Utilization (%) | Productivity (m³/SMH) | Cost ($/m³) |
|-----------------|-----------------------|-------------|
| 50              | 4.99                  | 31.83       |
| 60              | 5.99                  | 26.53       |
| 70              | 6.99                  | 22.74       |
| 80              | 7.98                  | 19.89       |
| 90              | 8.98                  | 17.68       |
| 100             | 9.98                  | 15.92       |

*Means productivity (m³/SMH) when machine utilization is 100% with no delay time.

$\text{Cost} = \frac{\text{Machine utilization}}{100} \times \frac{\text{Yarding rate}}{\text{Machine costs}}$

Where:
- **Machine utilization (\%)**
- **Yarding rate ($/m³)**
- **Machine costs ($/SMH)**

### Table 7. Delays observed during the study in four different study sites.

| Site | Item (unit: sec/cycle) | A | B | C | D |
|------|-----------------------|---|---|---|---|
| **Mechanical delays** | Carriage battery changes | 48 | – | – | – |
| | Remote control battery changes | – | – | 3 | – |
| | Breakdown of carriage | 13 | 29 | – | 43 |
| | Breakdown of machine | – | 16 | – | – |
| | Pressure regulation of carriage | 6 | 40 | – | – |
| | Checking | 3 | – | – | – |
| | Repair | 2 | – | – | – |
| | Sum | 72 | 85 | 3 | 43 |
| **Operational delays** | Re-checking | 10 | 12 | – | – |
| | Hang-up in stumps | 9 | – | 5 | – |
| | Hang-up in logging residue | 9 | – | – | – |
| | Hang-up in felling trees | – | – | 3 | 7 |
| | Wires hang-up | – | – | 36 | 14 |
| | Waiting | – | 23 | – | 13 |
| | Re-position of carriage | – | – | – | 13 |
| | Sum | 28 | 33 | 44 | 47 |
| **Personal delays** | Rest | 16 | 13 | 10 | 6 |
| | Total | 116 | 131 | 57 | 96 |

$\text{Delays} = \frac{\text{Machine utilization}}{100} \times \frac{\text{Yarding rate}}{\text{Machine costs}}$

Where:
- **Machine utilization (\%)**
- **Yarding rate ($/m³)**
- **Machine costs ($/SMH)**

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E-ISSN 2158-0715 FOREST SCIENCE AND TECHNOLOGY

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5%, it was confirmed that there is no statistically significant difference between the yarding productivity estimated with the regression equation developed in this study and the productivity experimentally measured on site.

Equation (4), derived using the full data \( n = 230 \), was then established as the final yarding productivity regression equation for HAM300.

Yarding productivity \( \left( \frac{m^3}{PMH} \right) \)

\[
= 6.79 - 0.16LD - 0.05YD + 9.77TV \quad \left( R^2 = 0.75 \right)
\] (4)

Since the \( p \)-values for predictor variables show differences less than the significance level of 5%, each of the variables included in the final regression equation was higher than those of previous studies (Han 2008; Cho et al. 2016), and the proposed regression equation may be used to estimate yarding productivity when HAM300 is used to harvest larch trees.

**Sensitivity analysis on key yarding variables**

To find out the factors that determine yarding cost using the final yarding productivity regression equation, a sensitivity analysis was performed on lateral yarding, yarding distance, and tree volume.

First, for the analysis of yarding productivity and cost increase/decrease rates depending on lateral distance, the values of the mean yarding distance (78.06 m), mean tree volume (0.92 m\(^3\)/cycle), and equipment cost ($278.66/PMH) were applied. The yarding productivity decreased by 0.9 m\(^3\)/PMH as the lateral distance increased by 5 m, starting from zero lateral distance, and the yarding cost increased from $23.55/m\(^3\) to $43.33/m\(^3\) at the increased rate of $0.50/m\(^3\) per one meter of lateral distance (Figure 1).

Second, for the analysis of yarding productivity and cost increase/decrease rates depending on yarding distance, the mean values of the other independent variables, lateral distance, tree volume, and equipment cost, were fixed at 9.13 m, 0.92 m\(^3\)/cycle, and $278.66/PMH, respectively. The yarding productivity decreased by 1.0 m\(^3\)/PMH as the yarding distance increased by 20 m, starting from zero yarding distance, and the yarding productivity increased from $19.78/m\(^3\) to $39.30/m\(^3\) at an increased rate of $0.10/m\(^3\) per one meter of yarding distance (Figure 2).

Finally, for the analysis of yarding productivity and cost increase/decrease rates depending on tree volume, the mean values of the other independent variables, namely, lateral distance, yarding distance, and equipment cost, were fixed at 9.13 m, 78.06 m, and $278.66/PMH, respectively. The yarding productivity increased by 1.9 m\(^3\)/PMH per unit tree volume of 0.18 m\(^3\), and the yarding productivity increased from $19.78/m\(^3\) to $39.30/m\(^3\) at an increased rate of $0.10/m\(^3\) per one meter of yarding distance (Figure 3).

From the overall analysis of the influence of each factor on a cable yarding operation using a HAM300, tree volume was found to exert the greatest influence on yarding cost, followed by lateral distance and yarding distance.

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**Table 7.** The preliminary regression equation to estimate the yarding productivity

| Classification | Regression equations                      | \( n \) | \( R^2 \) | \( p \) value |
|----------------|------------------------------------------|--------|---------|-------------|
| Total sites    | Productivity \( \left( \frac{m^3}{PMH} \right) = 6.23 - 1.78 \times LD \) | 152    | 0.74    | <0.0001     |
|                |                                            |        |         |             |
|                | \( -0.05 \times YD \)                    |        |         | <0.0001     |
|                | \( +10.33 \times TV \)                   |        |         | <0.0001     |
|                | **Total combined**                        |        |         |             |
|                | Productivity \( \left( \frac{m^3}{PMH} \right) = 6.79 - 0.16LD - 0.05YD + 9.77TV \) |        |         |             |

a : lateral distance (m).
b : yarding distance (m).
c : tree volume (m\(^3\)/cycle).
Conclusions

This study was conducted to calculate the cost of yarding operation using the HAM300 developed in South Korea at clearcut sites of larch stands located in Pyeongan, Gogil, and Ungyo in Pyeongchang, South Korea. We also developed a yarding productivity regression equation in an effort to provide basic data useful for setting up a HAM300 cable yarding. The combined average yarding productivity was calculated at 5.7 m³/SMH, with those of individual sites ranging from 4.2 m³/SMH to 6.3 m³/SMH; therefore, higher stability of equipment performance and task competence were positively associated with yarding productivity. Yarding productivity and the machine utilization rate were found to be correlated. Therefore, yarding productivity could be increased by improving the machine utilization rate through efficient operational planning, e.g. corridor layout considering the given topographic conditions, pre-inspection and post-maintenance/management of the yarder system, and specialized technical training to enhance task competence, in order to reduce the time for tower yarder setup and displacement and mechanical and operational delay.

The combined mean yarding cost was calculated at $27.91/m³. This relatively high cost can be ascribed to the low-machine utilization rate of the HAM300 (which is at an early development stage) in the yarding operations. This implies that low-cost yarding operations can be achieved by raising the machine utilization rate to 80% or higher by enhancing task competence through a targeted training of specialized professional workforce and management education. Analyses of the factors influencing yarding cost with the proposed yarding productivity regression equation revealed that tree volume had the greatest influence, followed by lateral distance and yarding distance.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by ‘A Study on the Development of Large-diameter log Harvesting Operation System and Safety of Work. [No. FO0100-2014-01-2015]’ funded by National Institute of Forest Science. This study has also been worked with the support of a research grant of Kangwon National University in 2016.

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