Performance Comparison for Two Cable Extraction Machines in a *Larix kaempferi* (Lamb.) Carr. Plantation

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Abstract: Forests in Korea are mainly located in steep mountainous areas, where small-shovel-based extraction technology is widely used, with the level of mechanization undoubtedly low due to financial limitations. On this steep terrain, a better approach may be to use cable yarders, which can offer high revenues through cable-based extraction. Therefore, improving the efficiency of cable yarding activities in good-quality timber forests is necessary. The main objectives of this study were to (1) evaluate the productivity and cost of a cable yarder operation for tree-length clearcut treatment of a *Larix kaempferi* (Lamb.) Carr. stand and (2) compare the productivity efficiency of two yarder (K301-4 and HAM300) types. The productivity rates of the K301-4 ranged from 10.2 to 12.5 m³/productive machine hours, with corresponding costs of US $12.6–15.4/m³. The productivity of the HAM300 was 26% lower than that of the K301-4 for a 30% lower cycle log volume while yarding and a comparable lateral distance. This study provides insights to support production and management decisions in the forest supply chain associated with planning cable-yarding operations.

Keywords: clearcut harvesting; tree-length logging; cable yarder; time study technique; efficiency

1. Introduction

Commercial planting of deciduous needle conifer species, primarily the *Larix kaempferi* (Lamb.) Carr., also known as the Japanese larch (about 14,000 hectares (ha) in 2018, representing 30% of the total coniferous plantation area), is important due to its sustainable economic value in South Korea (hereafter Korea) [1]. These Japanese larch forests cover approximately 0.3 million ha, representing 18% of the total coniferous forests (1.7 million ha), with an average stand volume of 172 m³/ha in 2018. This stand volume exceeds that of other conifer species (160 m³/ha in 2018). Previous studies including Cáceres et al. [2], Nagamitsu et al. [3] and Marmet et al. [4] reported that the genus *Larix* is resistant to climatic changes, exhibits rapid juvenile growth, and provides wood for many products (e.g., lumber, pulp and paper). Therefore, the Japanese larch contributes high-quality timber with a high market value in Korea.

The mechanization of timber harvesting commonly involves several challenges: the required equipment is costly [5], and the harvesting activities considerably disturb the forest soil through compaction, rutting and displacement [6]. These activities are even more difficult to conduct on steep terrains due to their inaccessibility to forest vehicles [7]. An alternative is to pursue the cable-based yarding operation. With this technology, negative environmental impacts would be reduced. For example, this concept is more appealing than ground-based harvesting since it eliminates the costs of constructing extensive road networks and environmental compliance [8]. In fact, cable yarding is commonly utilized on high-value-yield stands to enhance productivity and cost effectiveness [6,9].
Thus, extending its usage to steep terrains can potentially ease operations, improve safety and lower cost. Further, by expanding cable-based yarding operations, environmental impacts may be considerably reduced.

In Korea, although approximately 80% of all forested areas are on steep terrains (>40% of the land surface), the timber harvesting methods involve a combination of motor-manual felling, limbing, bucking and small-shovel-based extraction techniques [10]. The harvesting technology choice depends primarily on the financial resources, forest road network, forest machinery and available labor. Although changing from small-shovel-based techniques to cable yarding operations in steep terrains may enhance the productivity and forest management sustainability, their technical feasibility and economic efficiency are debatable [8,11]. In cable yarding activities, the HAM300 and K301-4 (Koller Forsttechnik GmbH Austria) yarders (Figure 1) are the most frequently used. The HAM300 is a cable yarder powered by a 60 kW farm tractor manufactured by the National Forestry Cooperatives Federation of Korea [12], whereas the 84 kW diesel engine two-axle truck-mounted K301-4 system is produced by Koller Forsttechnik GmbH.

![Exemplary cable extraction machines: (a1,a2) HAM300 yarder equipped with a HAM-C 1.0 remote controlled slack pulling carriage with a maximum load capacity of 1.0 tons, and (b1,b2) K301-4 yarder equipped with a Koller USKA 1.5 slack pulling carriage with a maximum load capacity of 1.5 tons.](image)

Several studies investigating the efficiency improvement of timber production and associated supply chain optimization using cable yarding systems exist. These studies involve understanding the efficiency of cable-based extraction technologies [13,14], decision-making [8,15] and compiling production models [16]. In most of these studies, however, the simulations are generally based on empirical data. Thus, utilizing decision techniques from these studies remains challenging since the machinery, stand features, corridor characteristics, and yarding direction comprising the cable-based extraction activities vary widely.

In Korea, no previous study has explicitly compared the HAM300 and K301-4 to highlight their differences and advantages. Many studies have rather focused on the productivity and operation of...
the HAM300 [12,17] and K301-4 [18]. In addition, the need for cost-effective technologies for steep terrain harvesting is increasing as cable-based extraction methods expand and improve. Consequently, the objectives of this study are to (1) evaluate the efficiencies of the HAM300 and K301-4 cable-based extraction machines in a Japanese larch plantation, (2) develop a general productivity model for the cable yarding method from many observations and (3) compare the performances of the cable extraction machines based on different site conditions. Our study improves the understanding of the effects of the stand and machinery on the performance of each extraction method. This knowledge can help forest managers properly evaluate harvesting costs and make informed decisions concerning Japanese larch stand management to maximize economic benefits.

2. Materials and Methods

The tests were conducted in six harvest units in the Gangwon region (37°02′–38°37′ N and 127°05′–129°22′ E; Figure 2) in the center of the eastern part of the Korean Peninsula from 2014 to 2016. For all the units, a time and motion study (TMS) was employed on the cable-based, tree-length (TL) clearcutting of the Larix kaempferi (Lamb.) Carr. harvest units. Although the TMS is generally conducted for just a short-term period, it is a common and vital tool for understanding the time consumption and productivity of individual harvesting machines [5]. For all stand inventories, the mean diameter at breast height (DBH) of the trees exceeded 32 cm, while the mean basal area ranged from 4.1 to 5.1 m²/ha (Table 1).

![Figure 2. Site map of the study harvest unit located in the Gangwon region, Korea.](image)

| Stand characteristics of the study harvest unit. |
|-----------------------------------------------|
| **K301-4** | **HAM300** |
| **Unit 1** | **Unit 2** | **Unit 3** | **Unit 4** | **Unit 5** | **Unit 6** |
| Area (ha) | 1.0 | 1.0 | 3.0 | 1.1 | 3.0 | 3.0 |
| Mean DBH (cm) | 37 | 37 | 34 | 32 | 34 | 34 |
| Mean height (m) | 26 | 23 | 23 | 22 | 23 | 23 |
| Basal area (m²/ha) | 5.0 | 5.0 | 4.7 | 4.5 | 4.5 | 4.6 |
| Trees per ha | 175 | 179 | 177 | 187 | 172 | 175 |

The TL harvesting operation comprised motor-manual felling, limbing and topping at the stump and cable yarding from the stump to the landing using two yarders (K301-4 and HAM300). The yarders used for extraction, according to the studied stands, are presented in Table 2. The TL logs were extracted uphill to the landing or roadside, with the yarders transporting the profitable logs to the landing.
while the toppings and residues were left on the stumps. Most of the harvested trees yielded one or two logs averaging 20 m in length. During the operation, the yarder operator was replaced by a chaser at the landing. In addition, an experienced crew of three choker setters hooked an optimum load.

### Table 2. Specifications of the cable-based extraction machines.

|                  | K301-4       | HAM300       |
|------------------|--------------|--------------|
| Manufacturer     | Koller       | National Forestry Cooperatives Federation in Korea |
| Skyline drum capacity (m) | 400         | 350         |
| Skyline diameter (mm)      | 18.0        | 16.0        |
| Mainline drum capacity (m) | 450        | 350        |
| Mainline diameter (m)      | 9.0         | 9.5         |
| Haul-back line drum capacity (m) | 800       | 500         |
| Haul-back line diameter (mm) | 9.0        | 9.0         |
| Tower height (m)       | 8.8         | 7.3         |
| Carriage engine power (kW)       | 99          | 48 (tractor PTO) |
| Maximum pulling capacity (kN)  | 26          | 24          |
| Maximum pulling speed (m/sec) | 7.5         | 4.2         |

During the field tests, we recorded the total extraction cycle times for both machines using stopwatches. Independent variables, including the yarding distance, log diameter and length and number of logs, were also measured for each cycle. The yarding procedure was categorized into six main tasks, including the outhaul, lateral out, hook-up, lateral in, in-haul and unhook [19], with the installation and takeoff times excluded. In addition, for all logs of each study site, the small and large end diameter and length were measured for calculating the individual log volume.

The hourly cost (US $/scheduled machine hours, SMH) of each machine was estimated using standard machine rate measurement practices [20]. This cost is commonly divided into ownership and operating costs. In cost analysis, the ownership costs, also termed fixed costs, traditionally involve the depreciation, interest, insurance and taxes. Particularly, for comparing the operating costs, the assumed expected economic life was 1400 SMH/year [1]. An interest rate of 10% and a tax rate of 4% were used to evaluate the ownership costs (Table 3). Conversely, the operating costs, also known as variable costs, comprised fuel, lubrication, repair and maintenance costs, as well as wage and benefits. The overhead, indirect, profit allowance and shipping expenses were excluded from the hourly cost.

### Table 3. Extraction equipment purchase price, annual depreciation, utilization rate and ownership cost for total cost calculation.

|                | Purchase Price ($) | Annual Depreciation ($/SMH a) | Utilization Rate (%) | Ownership Cost ($/SMH a) |
|----------------|--------------------|--------------------------------|----------------------|--------------------------|
| K301-4         | 300,000            | 27,551                         | 70                   | 51.25                    |
| HAM300         | 134,000            | 12,306                         | 70                   | 22.89                    |

* a Scheduled machine hours.

Delay-free cycle times (DCT) data were used to construct productivity simulation models for evaluating the cable yarding activities of TL harvesting. We adopted the least squares linear regression technique, also known as linear regression for data analysis. This method has been employed for producing empirical models from large datasets involving independent variables [21]. The prediction equation obtained with the least squares method is preferable, although the regression results can be adversely affected because of outliers and multipolar data [22]. For each machine, we created two linear regression models to estimate the DCT and then compared the predicted and observed values using a paired t-test. During the model construction, two-thirds of the training data were randomly selected, while the remaining (one-third) data were used for model validation. All statistical analyses were performed using the R statistical software version 4.0.2.
After the regression analysis, we conducted a sensitivity analysis for the cable yarders to determine the responses of the yarding operations to different variables. We also tested the effects of these variables on productivity. To compare the performances of the yarders, the DCT changes were converted to productivity and cost patterns for different yarder activities. Thus, this test aided in understanding the impacts of these independent variables on the maximum productivity and least cost.

3. Results

3.1. Productivity and Costs of Cable-Based Extraction Operations

The DCT data varied widely for both cable-based machines in each unit (Table 4). Our results show that the K301-4 required substantially more time for a cycle than the HAM300 because it involved a higher yarding distance and cycle log volume. In addition, the average K301-4 yarding productivity values from harvest units 1, 2 and 3 were 12.3, 12.5, and 10.2 m$^{3}$/productive machine-hours (PMH), respectively (yarding distance ranged from 12 to 215 m; Table 4). The productivity values of individual unit operations differed by up to 20% for similar stands. The estimated production cost, including the sum of ownership, operation and labor costs, ranged between US $12.6 and 15.4/m$^{3}$.

On average, the HAM300 machine produced 8.9 to 9.8 m$^{3}$/PMH at conditions of US $12.8 and 14.1/m$^{3}$, respectively (yarding distance ranged from 9 to 137 m). The productivity and costs slightly differed between the harvest units, ranging from 2 to 9% (Table 4), but these values were lower than those for the K301-4 tests. Further, the operating conditions such as the cycle log volume, yarding distance and lateral distance were statistically the same for each test (K301-4 test: unit 1 vs. 2 vs. 3; HAM300 test: unit 4 vs. 5 vs. 6).

| Table 4. Mean delay-free cycle times observed by cable extraction machines. |
|---------------------------------------------------------------|
| K301-4 | HAM300 |
| Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 5 | Unit 6 |
| Number of cycle times | 86 | 98 | 162 | 64 | 72 | 108 |
| Machine cycle time | | | | | | |
| Mean (sec/PMH) | 317 | 280 | 342 | 282 | 319 | 288 |
| Standard deviation | 68.82 | 66.88 | 118.73 | 78.87 | 63.92 | 71.92 |
| Productivity (m$^{3}$/PMH) | 12.3 | 12.5 | 10.2 | 9.1 | 9.8 | 8.9 |
| Cycle log volume (m$^{3}$) | 1.1 | 1.0 | 1.0 | 0.7 | 0.9 | 0.7 |
| Yarding distance (m) | 94 | 61 | 118 | 63 | 75 | 89 |
| Cost (US$/m$^{3}$) | 12.8 | 12.6 | 15.4 | 13.8 | 12.8 | 14.1 |

* Productive machine-hour.

The performances of the cable yarders also differed considerably, with the average productivity of the K301-4 operation about 26% higher than that for the HAM300. The 1.01 m$^{3}$ of logs per cycle transported on average by the K301-4 was approximately 32% higher than the 0.76 m$^{3}$ of logs hauled by the HAM300, creating a statistically significant difference between the operations (p-value = 0.0155). The average yarding and lateral distances of 91 and 11 m, respectively, for the K301-4 operation tests, surpassed the corresponding 75 and 9 m for the HAM300 by 20%, without any statistically significant difference between the machines (p-value > 0.05).

3.2. Delay-Free Cycle Time Regression Models

Prior to the least squares regression analysis, we blended the DCT data from the harvest units into a predictive equation for each yarding technology. Evidently, no statistically significant differences were found to exist among the sites (p-value > 0.05) for individual variables and the DCT regression equations and ranges of independent variables for each machine are presented in Table 5. Clearly, all models were significant, with no serious violations at the 1% significance level (p-value < 0.01),
and most of the independent variables were significant ($p$-value < 0.05). However, the trees per cycle was not a significant variable in the K301-4 yarding operation ($p$-value > 0.05), whereas, in the HAM300 model, the cycle log volume was the only non-significant variable ($p$-value = 0.403). For all DCT equations, after a paired $t$-test, the predicted DCT values did not have any statistically significant difference with the observed values ($p$-value > 0.05).

### Table 5. Delay-free cycle time regression equations for K301-4 and HAM300. Moreover, a paired $t$-test was used for equation validation against observed data.

| Parameter          | Range Variable    | Estimate | SE   | $t$     | $p$-Value | Model adj. $R^2$ | Model $p$-Value | $t$-Test |
|--------------------|-------------------|----------|------|---------|-----------|------------------|----------------|----------|
| K301-4             | Intercept         | 95.694   | 19.806 | 4.832   | <0.01     | 0.5934           | <0.01          | 0.4079   |
| Cycle log volume (m$^3$) | 0.2–2.4           | 34.489   | 10.184 | 3.386   | <0.01     |                  |                |          |
| Yarding distance (m) | 12–215            | 1.206    | 0.076 | 15.702  | <0.01     |                  |                |          |
| Lateral distance (m) | 0–46              | 4.889    | 0.487 | 10.030  | <0.01     |                  |                |          |
| No. of trees per cycle | 1–2              | 14.901   | 15.110 | 0.986   | 0.325     |                  |                |          |
| HAM300             | Intercept         | 128.420  | 18.535 | 6.928   | <0.01     | 0.4813           | <0.01          | 0.2042   |
| Cycle log volume (m$^3$) | 0.2–2.0           | 11.167   | 13.321 | 0.838   | 0.403     |                  |                |          |
| Yarding distance (m) | 9–137             | 1.041    | 0.111 | 9.353   | <0.01     |                  |                |          |
| Lateral distance (m) | 0–40              | 4.726    | 0.606 | 7.794   | <0.01     |                  |                |          |
| No. of trees per cycle | 1–2              | 28.897   | 13.922 | 2.076   | <0.05     |                  |                |          |

### 3.3. Sensitivity Analysis

We performed a sensitivity analysis to evaluate the impact of the yarding distance on the K301-4 and HAM300 models. The productivity of each machine changed with the yarding distance from 10 to 200 m in 5 m increment distance (Figure 3). The calculation was conducted under the following conditions: lateral distance of 10 m, cycle log volume of 0.9 m$^3$ and a trees-per-cycle value of 1. Overall, the estimated productivity decreased, and the cost increase as the yarding distance increased in both models.

![Figure 3](image-url)

**Figure 3.** Changes in extraction productivity (left $y$-axis) and production cost (right $y$-axis) over different yarding distances by the K301-4 and HAM300 machines.

The sensitivity analysis enabled the evaluation of the break-even yarding distances of the two machines. The productivity values for the K301-4 were higher for yarding distances less than 135 m,
while the costs were higher for all yarding distances compared with the HAM300 (Figure 3). This is because the purchase price of the K301-4 was more than two times that of the HAM300 yarder.

Further, we evaluated the impact of the cycle log volume on the performances of both machines (Figure 4). The productivity of each machine changed with yarding distances from 10 to 200 m under the following conditions: lateral distance of 10 m, cycle log volume between 0.9 and 1.5 m$^3$ and one tree per cycle. Overall, the estimated productivity increased as the cycle log volume increased for both models. Even if the DCT was longer for yarding a large cycle log volume, the productivity increased for both machines because of the payload per turn. In addition, the HAM300 exhibited higher productivity values for yarding distances higher than 55 m.

![Graph showing productivity and cost comparison](image)

**Figure 4.** Changes in extraction productivity as a function of cycle log volume over different yarding distances by the K301-4 and HAM300 machines.

### 4. Discussion and Conclusions

An efficient solution for timber harvesting in a steep terrain should be primarily connected to cable operations. During the last two decades, these technologies have been widely employed in Europe and North America, while extraction in Korea has commonly involved a small-shovel harvesting system due to financial limitations. Although cable yoders are used for harvesting timber under variable conditions, the planning and design remain poor. Therefore, this study involved the following: (1) evaluating the productivity and costs associated with the K301-4 and HAM300, (2) developing productivity models using the least squares linear regression technique and (3) comparing the performances of the cable-yarding machines based on different site conditions.

The production rates (10.2–12.5 m$^3$/PMH) for the K301-4 was approximately 25% higher than those for the HAM300 (8.9–9.8 m$^3$/PMH), with the operation cost correspondingly higher. In addition, for yarding distances less than 135 m at 0.9 m$^3$ cycle log volume, the K301-4 model yielded more productivity. Furthermore, the performance of the cable yoders changed in response to the cycle log volume and K301-4 potentially performed better for yarding distances less than 55 m when the cycle log volume was 1.5 m$^3$.

We showed that the productivity of each cable-based extraction operation (K301-4 and HAM300) varied by up to 20% between the three harvest units, with the performance differences linked to many reasons. For example, Lindroos and Cavalli [16], Erber et al. [23] and Schweier et al. [24] reported that the productivity variation in cable yarding operations was due to several reasons such as...
as working conditions and load sizes. In our study, however, during the individual machine tests, the work conditions were similar for the three harvest units (units 1–3 and units 4–6). Several studies also indicate that the operator affects the harvesting equipment productivity more than the stand characteristics [25,26]. This is consistent with our results from tests with separate machine operators and chock setters during harvesting. Therefore, the performance of the yarders varied from 2% to 20%, consistent with the results in Kärhä et al. [27]. Thus, results can vary because of a cable yarding operation crew difference.

Our results imply that the heavier payload capacity of the K301-4 yarder offers a better performance as the yarding distance decreases compared to the HAM300, although its price is a limiting factor. The higher productivity efficiency of the K301-4 used in this study demonstrates its higher payload and faster line speed. According to Schweier et al. [24] and Engelbrecht et al. [28], the operation productivity was affected by the yarder type (heavy or medium) and piece size per cycle. The performance of the heavy yarder ranged from 20% to 30%, depending on the inclusion or exclusion of delay times, since the performance continuously improved with the cycle speed and payload. The differences in rates between the K301-4 and HAM300 in this study coincide with results from previous studies. For the K301-4 yarder, the higher productivity is attributed to its ability to haul large pieces of logs in a single cycle. Thus, the performance of the cable yarding operation is sensitive to the machine type.

We also evaluated the impact of the cycle log volume on the productivity for each yarding operation. The log production advanced with increasing cycle log volume for both yarding operations. This finding is consistent with previous studies such as Engelbrecht et al. [28] and Hiesl and Benjamin [29] reporting that the extraction (including cable yarding and forwarding) productivity significantly increases with timber size (0.2–1.2 m³). The piece-volume has been reported earlier in many studies, such as Berendt et al. [6] and Ghaffariyan [30]. Their findings were that larger log sizes could increase the harvesting productivity, even though the time consumed per cycle in mechanized harvesting also increases. Consequently, the cycle log volume can considerably affect the productivity in cable extraction activities.

Transportation between a stump and a landing or forest roadside in steep terrain is technically difficult and expensive in terms of wood production. These may impact directly and indirectly change forest ecosystems and environments, such as soil, air, water, biodiversity and regeneration capacity. Therefore, adequate planning, including decision support technology for yarding/skidding, may be necessary to provide precise information for identifying the preferred conditions. Application to widely different conditions using empirical productivity models remains challenging [5,16,28]. Even though the validity of the empirical models may be limited to the K301-4 and HAM300 yarder configurations in this study, the results can highlight preferential conditions such as the yarding distance and cycle log volume for the cable extraction method selection. Further studies are needed to investigate improving the accuracy of the models based on spatial considerations. In addition, studies comparing timber supply chains (cable-based harvesting system vs. ground-based harvesting system) are also necessary to improve knowledge on the sustainability of the wood supply chain.

In conclusion, in this study, the performances of two yarder types (yarder mounted on a truck: K301-4 and yarder mounted on a tractor: HAM300) deployed in different harvest units were investigated. The K301-4 yarder operation involved a larger cycle log volume than that for the HAM300. Our results demonstrated that machine type considerably affected cable extraction performance. In addition, for a cycle log volume of 0.9 m³ in our harvest units, the productivity of the K301-4 is higher up to 135 m, whereas it changes into a good performance option until 55 m when the cycle log volume is 1.5 m³. Replications of the productivity models may be robust because the DCT data collected under different conditions involved many observations and long-term studies. Therefore, the models are potentially beneficial for evaluating the productivity of each machine and improving cable yarding planning. Future research should tackle the financial implications of the machine operating conditions (stand density, silvicultural prescriptions: thinning and partial harvest).
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